International Journal of Automotive Technology, Vol. 15, No. 2, pp. 203−218 (2014)
DOI 10.1007/s12239−014−0022−x

pISSN 1229−9138/ eISSN 1976−3832

REVIEW ON CHARACTERIZATION OF NANO-PARTICLE EMISSIONS AND PM MORPHOLOGY FROM INTERNAL COMBUSTION ENGINES: PART 1

C. L. MYUNG, A. KO and S. PARK*

School of Mechanical Engineering, Korea University, Seoul 136-701, Korea

(Received 18 October 2013; Revised 13 November 2013; Accepted 3 January 2014)

ABSTRACT−This paper is review of the characterization of exhaust particles from state-of-the-art internal combustion engines. We primarily focus on identifying the physical and chemical properties of nano-particles, i.e., the concentration, size distribution, and particulate matter (PM) morphology. Stringent emissions regulations of the Euro 6 and the LEV III require a substantial reduction in the PM emissions from vehicles, and improvements in human health effects. Advances in powertrains with sophisticated engine control strategies and engine after-treatment technologies have significantly improved PM emission levels, motivating the development of new particle measurement instruments and chemical analysis procedures. In this paper, recent research trends are reviewed for physical and chemical PM characterization methods for gasoline and diesel fueled engines under various vehicle certification cycles and real-world driving conditions. The effects of engine technologies, fuels, and engine lubricant oils on exhaust PM morphology and compositions are also discussed.

KEY WORDS : Particulate matter, Gasoline direct injection, Engine lubricant, Filter regeneration, PM morphology

1. INTRODUCTION

The enforcement of more stringent vehicle emissions regulations, carbon dioxide (CO_2), and fuel economy (FE) standards has compelled automotive manufacturers to reduce pollutant emissions from vehicles and to develop energy-efficient internal combustion engines. The implementation of stricter emission standards in the transportation sector can make positive effects on improvement of urban air quality and human health (Denner, 2013; Schöppe *et al*., 2013).

The introduction of advanced vehicle emissions control technologies for gasoline, diesel, gas fuelled vehicles has resulted in a substantial reduction of hazardous air pollutants (HAPs), including both regulated and non-regulated harmful emissions. However, the steady growth of vehicle populations in metropolitan areas has resulted in frequent exceedances of the established environmental quality standards for ozone (O_3), particulate matter (PM), and nitrogen oxides (NOx) (Eastwood, 2008; Lu *et al*., 2012; Myung and Park, 2012; Rahman *et al*., 2013).

Many studies have shown that there are substantial differences in the fuel consumption and exhaust emissions between vehicle certification modes and on-road driving testing in the European Union (EU), therefore, a new driving cycle known as the worldwide-harmonized light-duty test cycle (WLTC) was developed to accurately reflect real-world vehicle driving patterns. Furthermore, a complementary emission test procedure was introduced that simulates real-world operating conditions, i.e., portable emissions measurement systems (PEMS) testing, which are considered to be the most promising measures for reducing actual gaseous tailpipe emissions from engines and vehicles (Kirchner *et al*., 2013; Johnson *et al*., 2011; Mock *et al*., 2013; Rakopoulos and Giakoumis, 2009).

There are significant opportunities for developing downsizing gasoline direct injection (GDI) engines and turbocharged diesel engines that meet global vehicle fuel economy and CO_2 emission standards. Regulated gaseous emissions, except particle number (PN) emissions, from GDI vehicles can be significantly reduced by using advanced three-way catalysts (TWCs) and stoichiometric operation (Arsie *et al*., 2013; Basshuysen, 2009; Hwang *et al*., 2012; Hassaneen *et al*., 2011; Momenimovahed *et al*., 2013). The use of a diesel particulate filter (DPF) with a diesel oxidation catalyst (DOC) in new diesel engine results in PM and PN emission levels that are comparable to those from port fuel injection (PFI) engines and much lower than those from GDI engines (Brijesh and Sreedhara, 2013; Eiglmeier *et al*., 2011; Giechaskiel *et al*., 2012, 2014; Wang *et al*., 2012). However, many studies have reported that considerable nano-particle emissions are produced by vehicles operating under transient running conditions at cold ambient temperatures and during particle regeneration periods. Several studies have also shown that

**Corresponding author.* e-mail: spark@korea.ac.kr

PM formation from internal combustion engines can be substantially reduced via a combination of engine hardware modifications, precise air-fuel mixture preparation, and sophisticated engine control strategies during transient engine operations (Basshuysen, 2009; Fan *et al*., 2012; Kim *et al*., 2013b; Neußer *et al*., 2013; Ohm, 2013; Rakopoulos and Giakoumis, 2009; Zhao, 2010).

Carbonaceous PM particles from internal combustion engines are composed of various harmful substances, and their particle size distributions, morphologies, and chemical compositions have been characterized in detail (Barone *et al*., 2012; Gaddam and Vander Wal, 2013; Paul *et al*., 2013). The nanostructure of PM particles depends on various engine operating conditions and after-treatment devices, which has motivated the development of microscopic evaluation techniques, i.e., scanning electron microscopy (SEM) and transmission electron microscopy (TEM) (Burtscher, 2005; Bzdek *et al*., 2012; Eastwood, 2008; Maricq, 2007; Lee *et al*., 2013a). Recently, there has been growing concern regarding engine oil-derived PM emissions, which are associated with increasing vehicle mileage accumulation and the deterioration of after-treatment performance. Combustion byproducts of engine oil containing various additives cause soot and ash deposits in the combustion chamber and after-treatment devices, and deteriorate the durability of the after-treatment systems. The inhalation of ultrafine particles of mixed heavy metal elements has adverse human health effects (Brandenbergera *et al*., 2005; Eastwood, 2008; Jung *et al*., 2003; La Rocca *et al*., 2013; Liati and Eggenschwiler, 2010; Shim *et al*., 2013).

The EU has proposed a solid particle PN (#/km) limit in Euro 6b and Euro 6c, which will be enacted in September 2014, for the type-approval of GDI light-duty vehicles (LDVs) of 6.0×10^{11}-6.0×10^{12} (#/km) from 2014 to 2017 and 6.0×10^{11} (#/km) from 2017, respectively. The PN limit in Euro 5b of 6.0×10^{11} (#/km) for compression ignition (CI) LDVs has already been implemented as in September 2011. The test procedure for the PM mass (mg/km) emissions limit has been defined in United Nations Regulation 83 as 4.5 mg/km for both GDI and diesel passenger vehicles in the Euro 5b standard. The PN (#/kWh) limits in Euro 6 for type-approval heavy-duty (HD) diesel engines were implemented in December 2012 and are as follows: 6.0×10^{11} (#/kWh) for the worldwide heavy-duty transient cycle (WHTC) and 8.0×10^{11} (#/kWh) for the worldwide heavy-duty steady-state cycle (WHSC). The PM mass (mg/kWh) limit in Euro 6 was 10 mg/kWh for both CI (WHSC and WHTC) and SI (WHTC) heavy-duty engines (Delphi, 2013; Fraidl *et al*., 2012; Ko *et al*., 2012; Mamakos *et al*., 2013a; Myung and Park, 2012).

The California Air Resources Board (CARB) proposed the LEV III standards and a phase-in schedule for particulate emissions of 3.0 mg/mile as of 2017 MY and 1.0 mg/mile as of 2025-2028 MY for passenger cars, light-duty trucks (LDTs) and medium-duty passenger vehicles. The current PM limit is 10 mg/mile for passenger vehicles, and the PN (#/mile) standards have now been eliminated from the proposal. Gasoline particulate filters (GPFs) are very effective measures for reducing both the PM mass and the PN concentration: CARB expects that almost all GDI vehicles with GPFs will clear the 1.0 mg/mile PM standard of the LEV III PM regulations very easily (CARB, 2010; Delphi, 2013; Mamakos *et al*., 2011; Myung and Park, 2012; Richter *et al*., 2012; Zhang and McMahon, 2012).

In this study, we review the particle formation and reduction mechanism in internal combustion engines to provide comprehensive measures for meeting stringent particle number and mass regulations worldwide. We also review trends for the physical characteristics, i.e., the size distribution and morphology, and the chemical composition of exhaust carbonaceous soot particles, as well as the properties of various automotive fuels, lubricant compositions, and after-treatment systems.

2. NANO-PARTICLE EMISSIONS FROM INTERNAL COMBUSTION ENGINES

2.1. Characterization of Particulate Matter

In June 2012, the World Health Organization (WHO) International Agency for Research on Cancer (IARC) reclassified diesel exhaust emissions as 'carcinogenic to humans', which triggered controversy among automotive manufacturers. The primary claims made by industries are that PM/NOx components have been reduced through substantial improvements in combustion and after-treatment technologies of new diesel fuelled vehicles, which when combined with the use of DPF, deNOx systems and ultra-low sulfur diesel (ULSD) fuel, produce emissions under the Euro 5 standards (Borge, 2013). However, significant levels of PM/NOx emissions exhausted from old diesel vehicles on the road can aggravate human health and urban air quality. Additionally, concerns persist on how effectively all of these technologies that meet Euro 6 legislative standards work for reducing off-cycle emissions in real-world vehicles

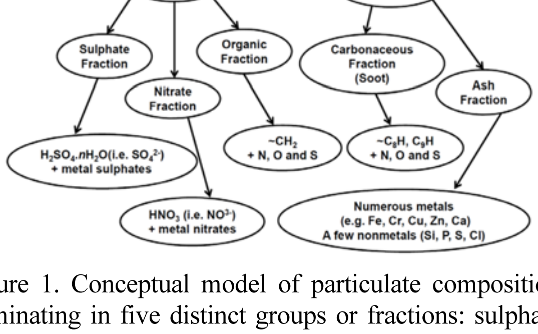

Figure 1. Conceptual model of particulate compositions, terminating in five distinct groups or fractions: sulphates, nitrates, organics, carbonaceous, and ash.

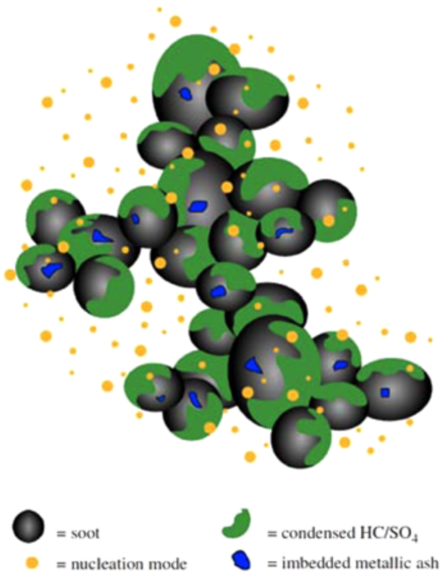

Figure 2. PM compositions from internal combustion engines.

running under sub-zero temperatures with aggressive acceleration and air conditioning (Bielaczyc *et al*., 2013; Fraidl *et al*., 2012; Mamakos *et al*., 2011; Mock *et al*., 2013; Myung *et al*., 2014; Ntziachristos *et al*., 2011).

Particles emitted from internal combustion engines are a complex mixture of volatile materials (organics, sulfates, and nitrate fraction) and non-volatile materials (soot and ash) as shown in Figure 1. Each PM fraction is closely related to the specifications of the fuels and the lubricants; the engine operating conditions, i.e., the load and the coolant temperature; the engine wear in terms of the mileage accumulation; and exhaust after-treatment technologies (Burtscher, 2005; Bzdek *et al*., 2012; Eastwood, 2008; Maricq, 2007). Carbonaceous soot particles are coated with metals and toxic compounds resulting from engine combustion, such as cancer-causing aldehydes and polycyclic aromatic hydrocarbons (PAHs) (see Figure 2). The use of instruments for measuring the physical characteristics (i.e., the size distribution, the microstructure, and morphology) and the chemical fraction (i.e., organic, carbonaceous, ash, etc.) of PM from exhaust emissions has been well established in several studies (Burtscher, 2005; Bzdek *et al*., 2012; Gaddam and Vander Wal, 2013; Giechaskiel *et al*., 2012, 2014; Liati *et al*., 2012; Lu *et al*., 2012; Vincent *et al*., 2007; Wang, *et al*., 2013).

2.2. PM Emissions from SI Engines

Automotive industries are developing turbo-charged direct injection spark ignition (DISI) engines to reduce fuel consumption and CO_2 emissions using down-sizing or down-speeding concepts. State-of-the-art GDI engines with boosting technology and high compression ratios can achieve higher specific power and lower fuel consumption than conventional PFI engines. Recent studies have shown that GDI engines produce significant levels of particulates compared to DPF-equipped diesel engines and PFI engines. For GDI vehicles to meet future PM and PN emissions, comprehensive approaches have been used including engine control strategies, combustion chamber design, high-pressure injection system, and gasoline particulate filters (GPFs) in extreme cases (Arsie *et al*., 2013; Basshuysen, 2009; Choi *et al*., 2013; Eastwood, 2008; Kern *et al*., 2013; Kufferath *et al*., 2012; Myung *et al*., 2012b).

Excessive nano-particle formation from GDI vehicles during the cold start phase and aggressive running can be substantially reduced by using an advanced fuel injection system and engine control strategies, such as the use of high injection pressure, multi-hole injectors, and split injections. These fuel injection systems enhance fuel vaporization and the air-fuel mixing quality, thereby preventing fuel wetting on the piston bowl and cylinder liner (Arsie *et al*., 2013; Basshuysen, 2009; Eastwood, 2008; Kern *et al*., 2013; Kufferath *et al*., 2012; Myung *et al*., 2012b). In general, increasing the injection pressure

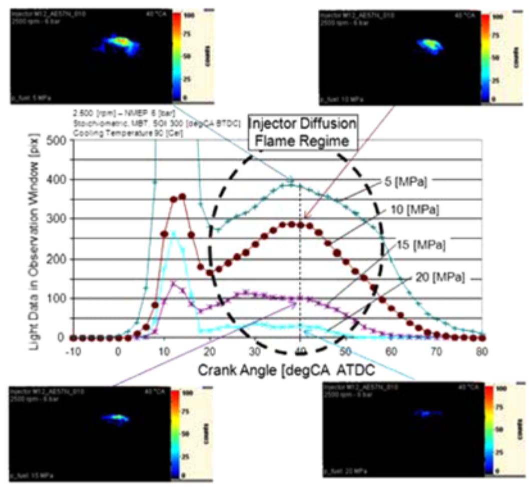

Figure 3. Flame intensity at 40 deg CA ATDC at various fuel pressures.

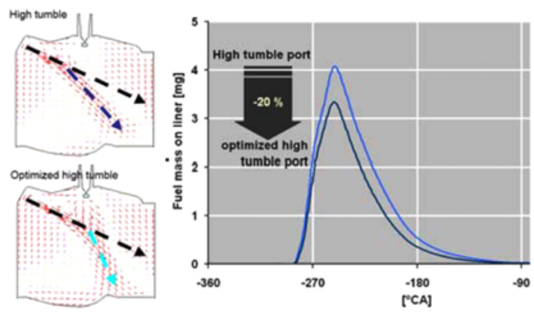

Figure 4. Fuel spray deflection using a high tumble port and a cavity piston.

reduces the Sauter Mean Diameter (SMD) of fuel droplets, which increases fuel evaporation and homogenizes air/fuel mixture. However, increased spray penetration can result in wall wetting and dilute the oil film on the cylinder wall (Berndorfer *et al*., 2013; Kim *et al*., 2013b; Kufferath *et al*., 2012). Figure 3 shows the effects of the fuel pressure on the flame intensity in a combustion chamber.

Reducing particulate emissions and oil dilution in a GDI engine requires careful design of the intake charge motion, the piston bowl shape, the injector locations, and spray targeting optimization. Many studies have shown that using fuel spray deflection with a high tumble port and a cavity piston enhance combustion stability and limit wall wetting in GDI engines (Basshuysen, 2009; Choi *et al*., 2012; Duchaussoy *et al*., 2011; Myung and Park, 2012; Ohm, 2013; Schöppe *et al*., 2013; Whitaker *et al*., 2011). Figure 4 shows that optimizing the tumble ratio can reduce the fuel mass on the liner by 20%.

The injection timing is one of the calibration parameters for mixture formation and particle emissions in a GDI engine. The start of injection (SOI) timing affects the fuel evaporation time and the local fuel build-up in a combustion chamber (Eastwood, 2008; Schöppe *et al*., 2013). Higher particle emissions are produced because less time is available mixture homogenization in GDI engines than in PFI engines. Furthermore, some fuel strikes the piston and the cylinder wall and accumulates as liquid films or pools, which ignite and burn with the diffusion flames. Kufferath *et al.* (2012) concluded that an adequate SOI, along with avoiding spray-piston or spray-wall contact, is necessary for particle emission reduction. Figure 5 shows the PN size distribution for the SOI.

Combining high fuel pressures with multiple injections during cold engine operation can significantly impact particle generation by improving the atomization and wall

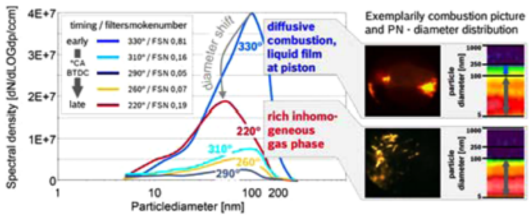

Figure 5. Tumble effect on fuel spray deflection and liner impingement at 1500 rpm/full load.

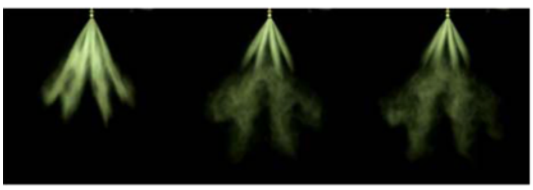

Figure 6. Injector spray visualization for single, double, and triple injection.

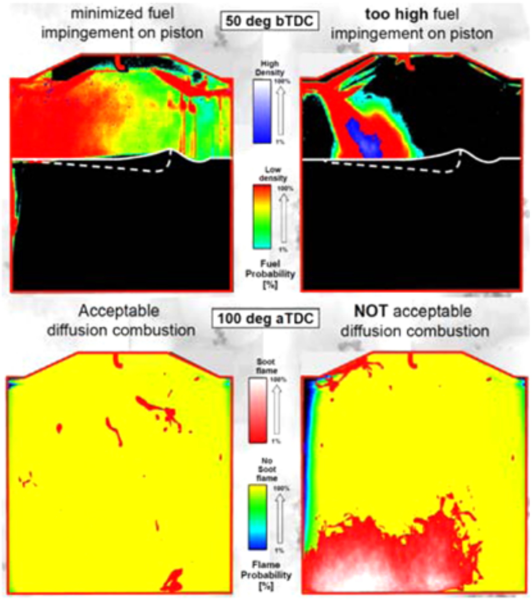

Figure 7. Optical visualization of mixture formation, combustion, and soot formation characteristics.

wetting characteristics of the fuel. The flame visualization results for a GDI engine show that the primary particle emissions sources are the very rich mixture zones, which form strong diffusion flames in the combustion chamber as in diesel engine combustion. Multiple injection strategies during the cold start and warm-up stage are used to minimize fuel impaction on the piston crown and the cylinder wall and to homogenize the mixture at the initial stage of combustion. Optimizing the SOI timing and using a precise split ratio with duration control between the injection pulses are very important calibration parameters for reducing PN emissions (Fan *et al*., 2012; Fraidl *et al*., 2012; Hassaneen *et al*., 2011; Kim *et al*., 2013b). Figures 6 and 7 show the effects of using an injection control strategy for mixture preparation on PN emissions.

Berndorfer *et al.* (2013) used endoscopic flame visualization to investigate diffusion combustion phenomena in centrally mounted injection GDI engines. The diffusion flame close to the injector tip of a clean was compared to that of a coked injector using a ten-hour coking cycle to build up a deposit on the tip surface under fired engine operation. Figure 8 shows the structure of the deposit after a coking test for a single cylinder engine. The injector diffusion flame form and the PN emissions increase as the fuel vapor stored in the deposits is released and burned in a combustion chamber. Laser-drilled machining and surface treatment by coating can be used to maintain superior injector performances by controlling the spray cone angle, the penetration and the droplet size, which impact vehicle mileage accumulation (Duchaussoy *et al*., 2011; Fraidl *et al*., 2012).

Recent research has shown that PN emissions can be

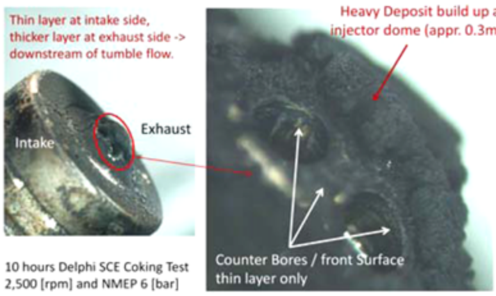

Figure 8. Structure of deposit on injector tip after a 10-hour coking cycle.

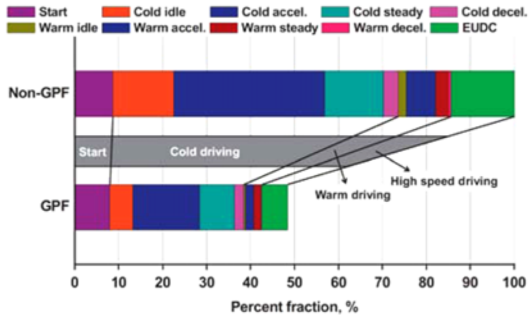

Figure 10. Fractions of nano-particle emissions at different engine temperatures and driving conditions for a GPF-equipped GDI passenger vehicle, measured using a DMS500 in the tailpipe position.

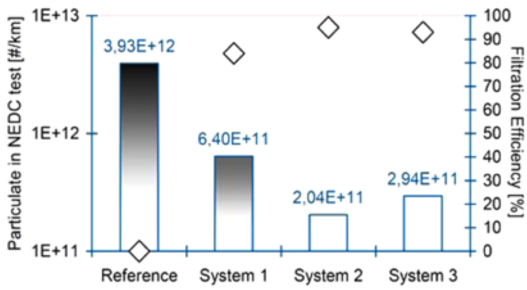

Figure 11. Filtration efficiency for a reference TWC vs. ‘add on’ option systems 1, 2, and 3 during NEDC testing: a) reference system, b) uncoated GPF in underbody position, c) coated GPF in underbody position, d) zoned close coupled TWC and coated GPF in underbody position.

reduced below the 2017 Euro 6c GDI vehicle limit of 6×10^{11} #/km by refined combustion mixture formation, engine hardware optimization, and sophisticated EMS calibration. Combining catalyst heating logic with high fuel pressures, split injections, and aggressive spark timing retard after top dead center (ATDC) for early three-way catalyst (TWC) activation, which is a key technology for reducing harmful exhaust emissions during the cold start and cold transient phase of GDI engines (Duchaussoy *et al*., 2011; Fraidl *et al*., 2012; Kim *et al*., 2013b, 2013c; Mamakos *et al*., 2011; Myung *et al*., 2012a, 2012b; Myung and Park, 2012; Zhang and McMahon, 2012). Figure 9 shows a PN reduction performance above 90% in the NEDC for a turbocharged GDI vehicle.

Installing a particulate filter in GDI vehicles is a straightforward way of reducing PN emissions to levels comparable to those from advanced DPF-diesel and PFI vehicles. Compared to DPF-diesel engines, GPF-GDI engines can be operated under more favorable conditions, such as higher exhaust gas temperatures for passive particle regeneration, lower soot accumulation, and faster GDI soot oxidation rates (which is 2.5 times higher than diesel soot oxidation). Low soot loading characteristics enable GPF systems to use more cost effective and compact filter designs than DPF-diesel systems (Mamakos *et al*., 2011). Additionally, the effect of vehicle performance loss on the engine power, fuel economy, and CO_2 emissions can be minimized by reducing the GPF pressure drop (Richter *et al*., 2012; Opitza *et al*., 2013). Figure 10 shows the PN reduction for engine temperatures and driving conditions using a metal-form-type GPF in the under-floor position of a GDI passenger vehicle. The PN emissions were measured using CPC for the NEDC and are 1.17×10^{12} #/km for the base GDI vehicle and 4.99×10^{11} #/km for the GPF-equipped GDI vehicle; the PN filtration efficiency is approximately 57% (Choi *et al*., 2013).

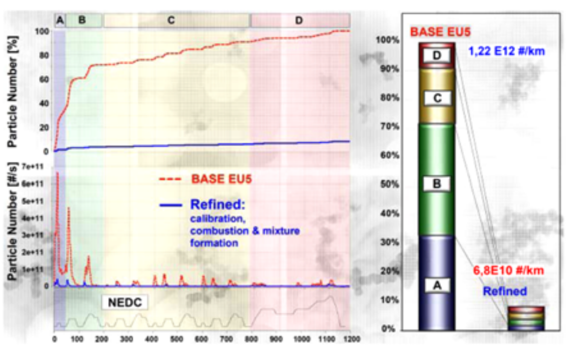

Figure 9. PN reduction in the NEDC for a turbocharged GDI vehicle.

Recent researches has shown that cordierite wall-flow catalyzed-GPFs with precious metal coatings have much higher PN filtration efficiencies in the NEDC than metal-form-type GPFs for turbocharged GDI passenger vehicles. Almost all of the PN emissions are primarily emitted during the cold start period and the acceleration cycle and are drastically reduced by using uncoated- and coated-GPFs. Applying a wash-coat to the filter increases the filtration efficiency 95% and 93% for systems 2 and 3, respectively, producing emission levels of 2.0×10^{11} #/km and 2.9×10^{11} #/km (Richter *et al*., 2012). The after-treatment system layout and the PN emissions for the GDI-

GPF are shown in Figure 11. A GPF could be an effective device for reducing particle emissions from a GDI engine, but both the power loss and the fuel economy penalty must be minimized by adjusting the pressure drop to optimize the GPF (Kern *et al*., 2013).

2.3. PM Emission from Diesel Engines

To meet the extremely stringent EU regulations on CO_2 95 g/km by 2020, automotive manufacturers have developed diesel passenger vehicles that achieve energy efficient powertrains while clearing Euro 6 exhaust emissions standards. NOx and PM exhaust emissions are the most challenging pollutants to treat in a diesel engine, and therefore several new technologies are being implemented to integrate air boosting management, combustion chamber design, fuel injection control, and after-treatment technologies (Sanchez *et al*., 2012; Rahman *et al*., 2013).

Recent diesel engines use turbo-boosted downsizing concepts to achieve low fuel consumption. Reducing the bore size of the engine decreases the distance from the injection spray to the piston cavity, thereby deteriorating the combustion efficiency and the PM emissions by forming a locally rich air-fuel mixture. Figure 12 summarizes the different methods for preventing particle formation by reducing a locally-rich mixture in a downsizing diesel engine (Omae *et al*., 2012; Yamano *et al*., 2013).

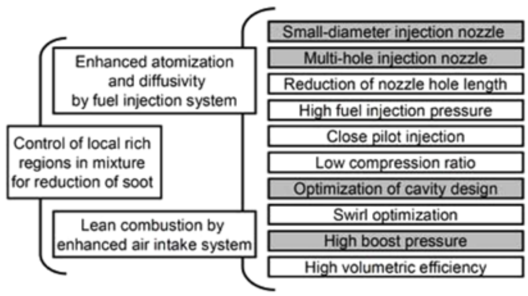

Figure 12. Strategies for enhancing combustion in a downsized engine.

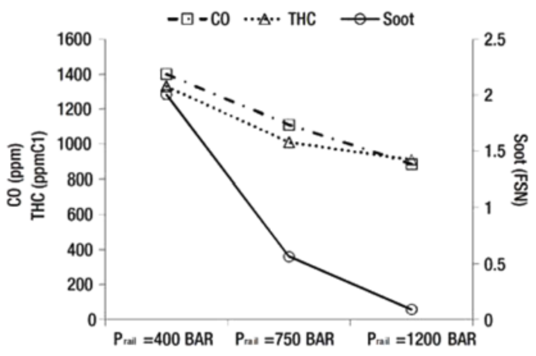

Figure 13. CO, THC and soot levels for different injection pressures; CO: carbon monoxide; THC: total hydrocarbon; FSN: filter smoke number.

Homogeneous charge compression ignition (HCCI) is known to be the most favorable combustion strategy for reducing both NOx emissions and PM emissions, because the local fuel-to-air equivalence ratio is sufficiently low to avoid soot formation, and the lean mixtures decrease the local flame temperature. Increasing the EGR rate decreases the NOx concentration by decreasing the O_2 concentration and the burnt gas temperature. However, HCCI prevents soot oxidation, and generally produces more PM as a result of the so-called PM-NOx trade-off (Brijesh and Sreedhara, 2013; Lee *et al*., 2013b, 2013c). The soot emission level drops significantly as the injection pressure increases primarily because of enhanced combustion mixing, which can significantly reduce soot-formable fuel-rich regions. Increasing the injection pressure prolongs the ignition dwell, which enhances fuel-air mixing processes both during and after injection and consequently significantly reduces the soot emissions in the premixed charge compression ignition (PCCI) condition. Figure 13 shows the CO, THC and soot levels for different injection pressures. The filter smoke number (FSN) was measured by an AVL 415S smoke meter (Choi and Min, 2013).

Increasing the fuel injection pressure over 2000 bar and performing multiple injections with a piezo injector is one of the most important ways of accelerating fuel distribution in the cylinder through improving fuel droplet formation, fuel vaporization, and mixing with air (Omae *et al*., 2012; Sakono *et al*., 2011). Figure 14 shows the mixture preparation scheme and the shape of the combustion chamber used to abate PM emissions.

HCs and CO from diesel engines are not as problematic as the emissions from engines running under lean operating conditions, in addition, these components are easily oxidized by DOCs. Diffusion combustion results in much higher engine-out PM emissions, because the time periods for fuel evaporation and mixing with air in a spontaneous combustion process are extremely short. Multiple fuel injection control strategies consisting of precise fuel metering with extremely high injection pressures and a refined piston bowl shape can control the carbonaceous particle emissions that form in the combustion process by improving fuel atomization and the impingement of the fuel-piston interaction. The DOC and DPF are effective after-treatment systems for reducing the HC, CO, and soluble organic fraction (SOF) of PM and solid particulates with soot emissions. In addition to DOC+DPF system for clearing the Euro 6 regulations on NOx emissions, a lean NOx trap (LNT) or a urea-selective catalyst reduction (SCR), or both systems could be installed (Sanchez *et al*., 2012; Neußer *et al*., 2013; Rakopoulos and Giakoumis, 2009; Zhao, 2010). Figure 15 shows diesel engine fuel injection equipment, control strategies and after-treatment systems that can be used to meet Euro 6 emissions regulations.

Diesel exhaust after-treatment systems of DPFs and

DOCs are standard equipment for reducing PMs and other pollutants. PM emissions primarily consist of solid particles (elementary carbon and soot) and attached volatile compounds (adsorbed HCs) or SOF. Organic compounds form from unburned fuel or engine lubricating oil. The sulfate fraction depends on the sulfur content of the fuel and the engine oil (Burtscher, 2005; Eastwood, 2008; Maricq, 2007). The main function of the DOC is the oxidation of HC and CO emissions and the volatile components of PM. The filtration mechanisms for soot particles in a DPF have been well established by many studies. The soot particles from diesel engines are usually much smaller than the filter pore size; thus, deep bed and soot cake filtration principles can be used to determine the soot loading status in the DPF walls. In a fresh DPF, several filtration mechanisms, i.e., filtration, deposition, Brownian diffusion, and interception, can be used for different particle size ranges: as the soot continues to build-up at the pore sites in the DPF channels, the particles deposited on the filter surface form a thin layer of soot-cake that significantly boosts the filtration efficiency (Beatrice *et al*., 2012; Konstandopoulos and Papaioannou, 2008). Figure 16 shows results from a computational model for soot deposition and the flow field in a porous wall of a SiC-DPF.

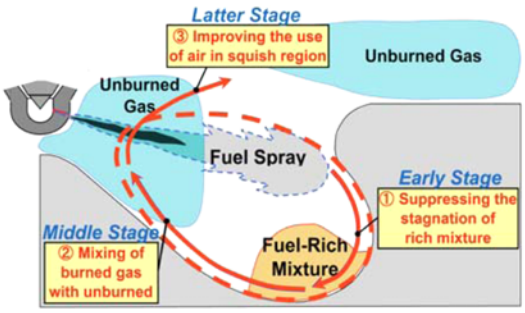

Figure 14. Egg-shaped combustion chamber and injection control strategy for diesel PM.

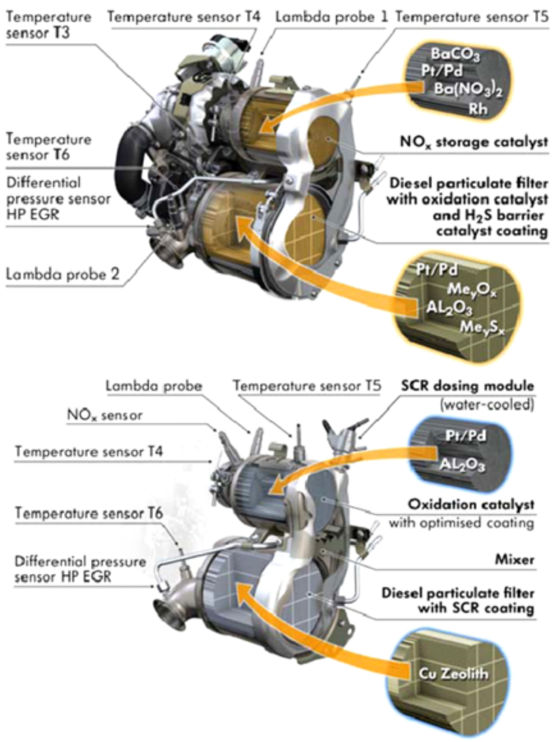

Figure 15. Exhaust system layout with DPF+NOx storage catalyst and DPF+SCR systems.

DPFs generally require periodical regeneration because of increments in the back pressure and exhaust flow restrictions after 300-800 km of vehicle operation, where the intervals depend on the amount of engine-out PM emissions and the DPF geometry.

The ratio of the DPF volume to the engine sweep volume ($V_{DPF}/V_{displacement}$) is typically 1.2-2.0. When the accumulated soot mass reaches approximately 5-10 g, and the pressure drop (Δ) between the inlet and outlet of the filter exceeds the DPF design target, the ECU regeneration logics are executed at intervals for the duration of the vehicle run to burn-off the deposited soot in the DPF walls and recover the engine performance (Eiglmeier *et al*., 2011; Kim *et al*., 2013a; Shim *et al*., 2013).

To raise the exhaust temperature for DPF regeneration, modern diesel engines that meet the Euro 5 emission standard use a fuel injection strategy consisting of a triple of post-injections during the late expansion stroke to generate exothermic energy across the DOC (Eiglmeier *et al*., 2011; Omae *et al*., 2012). During the regeneration stage, the filter temperature and the particulate concentrations sharply increase up to 700ºC and 1.6×10^8 (#/cm^3),

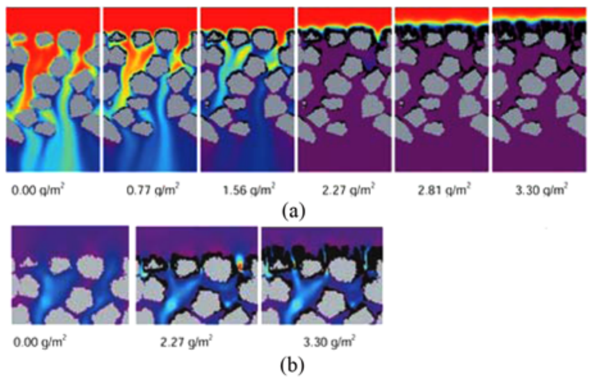

Figure 16. Visualization of soot deposition at different surface mass loads in an extruded ceramic (granular) filter wall: (a) development of soot deposits (black) and soot mass fraction in the wall (solid material is gray) at the onset of cake formation; the scale for the soot mass fraction scale ranges from 0 (violet) to the inflow value (red); (b) velocity in a section through the filter wall, overlaid with shape of soot deposit.

respectively, as shown in Figure 17. The nucleation mode particle under 30 nm sharply increases by approximately 2-4 orders of magnitude over normal operation (Beatrice *et al*., 2012). Figure 18 shows the PN concentrations during the regeneration events. Almost all of the particles are semi-volatile particles that can not be measured by instruments in the European particle measurement programme (PMP), which have a 23 nm cutoff.

The regeneration temperature for the filter materials is set to prevent thermal damage to the substrate. In abnormal regeneration, the DPF becomes loaded with heavy soot, resulting in filter overheating and cracking because of the high local oxidation rate of the substrate at very high interior temperatures of up to 1000ºC (Eastwood, 2008; Rakopoulos and Giakoumis, 2009; Sappok *et al*., 2010; Zhao, 2010). Ntziachristos *et al*. (2011) investigated the effect of filter crack patterns on particle emissions by using a particle sensor for the on-board diagnostics (OBD) of a DPF-equipped diesel engine and vehicle. The particle mass

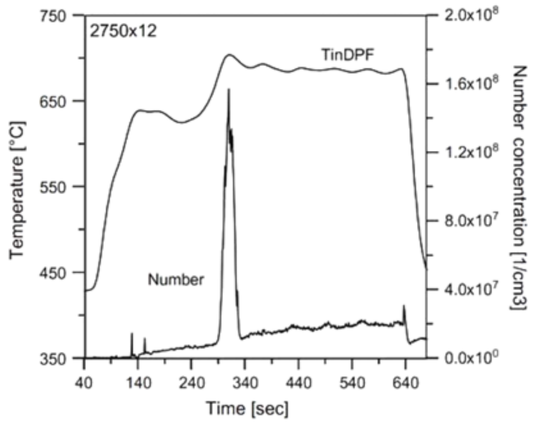

Figure 17. Temporal evolution of particle number concentration and temperature inside the DPF during regeneration, as measured by a DMS500 at 2750 rpm and 12 bar BMEP (engine displacement of 1956 cc, a close-coupled DOC and DPF for Euro 5).

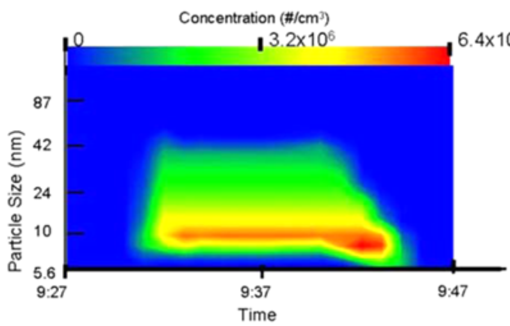

Figure 18. EEPS particle concentrations and size distributions during a regeneration event for a Peugeot 407 diesel passenger car with a DPF meeting Euro 4 emission standards.

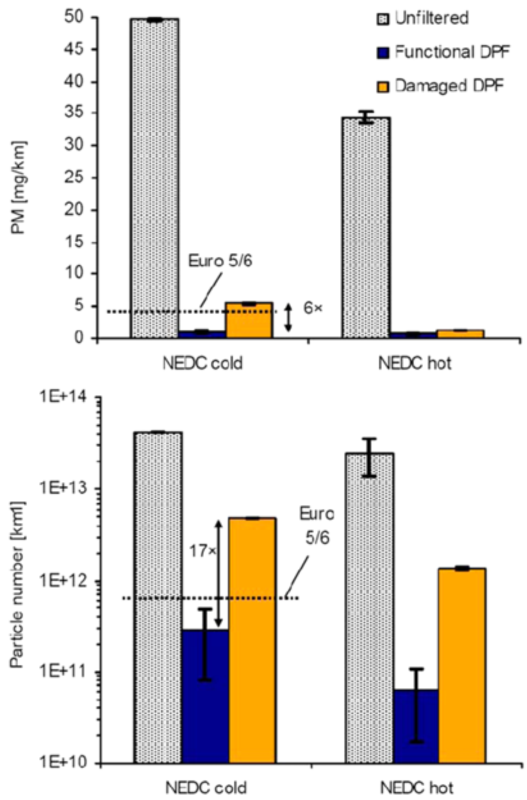

Figure 19. PM and PN emissions between functional and damaged SiC-DPF in NEDC mode.

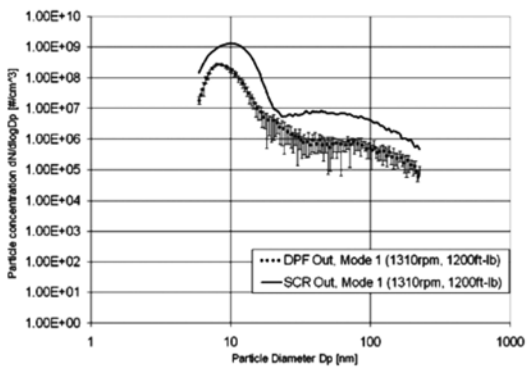

Figure 20. SMPS particle size distributions under steady operating conditions: 1310 rpm/1200 ft-lb, an exhaust temperature of 449ºC, and a urea dosage of 1.44 kg/h.

with a double ring-off crack of 6 mg/km is six times higher than that for a functional DPF of 1 mg/km over the cold NEDC. However, Figure 19 shows that the PN concentration for a functional DPF of 2.9×10^{11} (#/km) drastically increases (by 17 times) to 4.9×10^{12} (#/km) for a damaged DPF.

Investigating the effect of exhaust after-treatment systems on nano-particle emissions under real-world engine load conditions shows that nucleation mode particles below 6-15 nm are released at higher exhaust temperatures above 380ºC from a heavy-duty diesel engine with a 10.8 L displacement equipped with a DOC-DPF-SCR-AOC (ammonia oxidation catalyst) (Thiruvengadam *et al*., 2012). The PN concentration after SCR with urea injection increases the PN concentrations by over an order of magnitude compared to the after DPF out conditions, whereas engine operation below 380ºC does not contribute significantly to the nucleation mode particle concentration (see Figure 20).

Similar results have been obtained when the effect of the exhaust temperature on the PN size distribution is investigated for SCR-AOC systems operating in ETC and WHSC modes: high exhaust gas temperatures result in NO_2-assisted regeneration, which decreases the SCR reactivity. Generally, soot is regenerated above 300ºC, and a fast-SCR reaction occurs at 180-300ºC. Overdosing the urea injection quantity results in condensation of the slipped ammonia into the liquid phase through the tail-pipe and the sample line of the particle measurement system, such that nucleation mode particles between 5-20 nm are detected (Ko *et al*., 2012; Lee *et al*., 2012; Lu *et al*., 2012).

Microscopic analysis of the PM-loaded DPF sections shows that soot and ash components are deposited on the filter channel walls all along the filter length following regeneration (see Figure 21). The incombustible components of soot consist of inorganic metal compounds, such as oxides, hydroxides, and sulfates, among others, that remain in the filter after regenration as metal ash particles. It primarily originates from engine oil additives and partially from metals in the diesel fuel, engine wear and corrosion (Liati and Eggenschwiler, 2010; Liati *et al*., 2012). The PM distributions in DPF channels show that soot primarily accumulates at the inlet side of the DPF, after which a soot layer is deposited on an ash layer all along the channel.

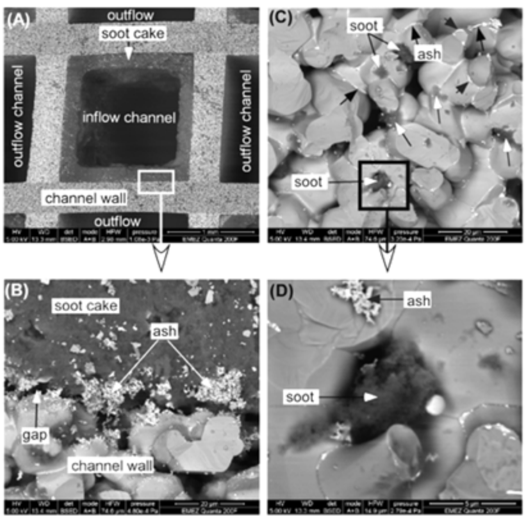

Figure 21. Back-Scattered Electron (BSE) images of a DPF inflow channel.

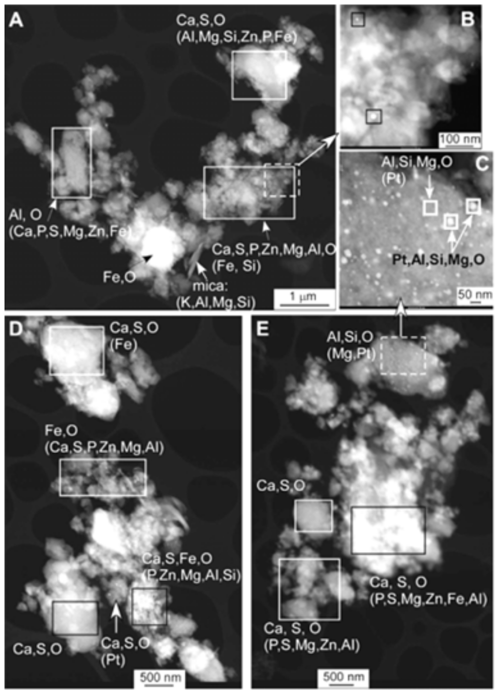

Figure 22. TEM images of ash agglomerates in a DPF.

Figure 22 shows TEM images of ash agglomerates for a DPF in a light-duty truck. Almost all of the ash has accumulated at the plugged ends of the inflow channels of the DPF. Chemical analysis shows that the ash parimarily consists of Ca, Mg, P, Zn, and S, which are oriented from lubricating additives and minor Fe, Al, and Si elements (Liati *et al*., 2012).

2.4. Effects of Engine Oil on PM Emissions

The particles from ICEs consist of elementary carbon (EC) and organic compounds, which originate from unburned lubricant oil, unburned fuel and partially oxidized compounds from engine oil and fuel. Small amounts of inorganic substance, i.e., sulfates and metallic salts, from lubricant additives are also present (Albuquerque *et al*., 2011; Brandenbergera *et al*., 2005). The functions of emission control systems of TWCs and DPFs with DOCs are significantly affected by the components of oil additives. Sulfur (S) and phosphorous (P) cause permanent chemical poisoning of the metallic surface of the wash-coat, whereas ash-forming additives such as zinc dialkyldithiophosphates (ZDDP) and detergents, block the DPF. These phenomena deteriorate exhaust emissions and increase the pressure loss in after-treatment devices. Thus, new lubricant formulations with lower concentrations of sulfated ash, phosphorous and sulfur (SAPS) in the lubricant are required for modern powertrains and exhaust after-treatment systems (Carvalho *et al*., 2010; Hoshino *et al*., 2005; Inagaki and Kondo, 2009).

Fully synthetic engine lubricating oils generally have lower sulfur contents (below 200-300 ppm) compared than mineral-based engine lubricating oils, which have sulfur contents ranging from 0.4 to 0.9%. In particular, calcium sulfate (gypsum) is released into the atmosphere during DPF regeneration and increases the particle concentration in the ambient air particles. Investigating the effects of the exhaust temperature on the ash composition and the properties of the ash layer shows that increasing the temperature above 700°C results in ash decomposition (Sappok *et al*., 2010). Low-sulfated diesel engine oil reduces ash deposition on the DPF and the pressure drop. Therefore, it can help extend the DPF maintenance period.

In ICEs, engine oil is consumed at the piston-ring liner, the valve stem seals, the positive crankcase ventilation (PCV) system, and the turbocharger. The oil consumption rates of each source are closely related to the engine operation conditions, i.e., the speed, the load and the temperature, and the engine oil specifications, i.e., the viscosity, the volatility and the additive compositions. The engine operating conditions significantly affect the detailed particulate matter composition and the transient engine operation, which cause most of the lubricating oil consumption (Stetter *et al*., 2003).

Several studies have shown that various lubricant properties of mineral oils and synthetic oils affect the volatile organic fraction, the sulfate and soot fraction (or the dry-particulates) of PM and the fuel economy. Additionally, soot entry into the engine lubricant through the oil film on the cylinder wall affects the viscosity; thus, dispersants are added to minimize agglomeration (Carvalho *et al*., 2010; Dong *et al*., 2013; Eastwood, 2008). The effect of engine oil on PM emissions can be summarized as follows: high oil viscosity and low oil volatility reduce the oil consumption and oil-oriented particulate emissions. A small proportion of PM produced by the combustion process is transferred into the engine oil, resulting in soot-in-oil phenomena. Diesel soot migrates into the oil film early in the expansion stroke, consequently, the morphology shows quite different characteristics to exhaust soot and influences on oil properties. Therefore, investigation on soot surface nanostructure is very important because soot reactivity and oxidation rates are influenced by the existence of defects and incomplete layers (La Rocca *et al*., 2013). Analyzing the primary exhaust soot particles by high-resolution TEM shows a primary particle size of 5−28 nm with an outer shell of 0−4 nm (see Figure 23).

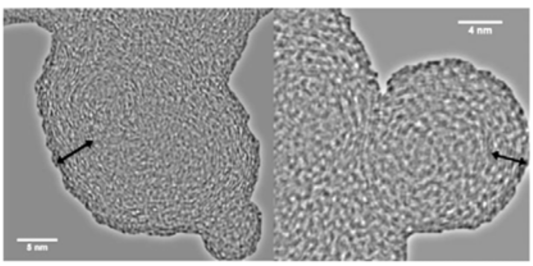

Figure 23. Exhaust primary particle (left: diameter D = 22 nm, outer shell: 3.8 nm, right: diameter 16 nm, outer shell: 3 nm).

The Collaborative Lubricating Oil Study on Emissions (CLOSE) project has investigated how fuels and crankcase lubricants contribute to the formation of PM and semi-volatile organic compounds (SVOC) in vehicle exhaust for LD gasoline cars, MD diesel trucks, and HD diesel and natural gas fueled buses. The results implicate engine lubricating oil as a significant parent material in the formation of mobile source PM emissions, including nanoparticle emissions (Carroll *et al*., 2011).

Fushimia *et al*. (2011) investigated size-resolved PN concentrations and the comprehensive chemical composition (i.e., the elemental and organic carbons, elements, ions, and organic compounds) by particle size in diesel exhaust to determine the fuel and oil contributions to nano-particle

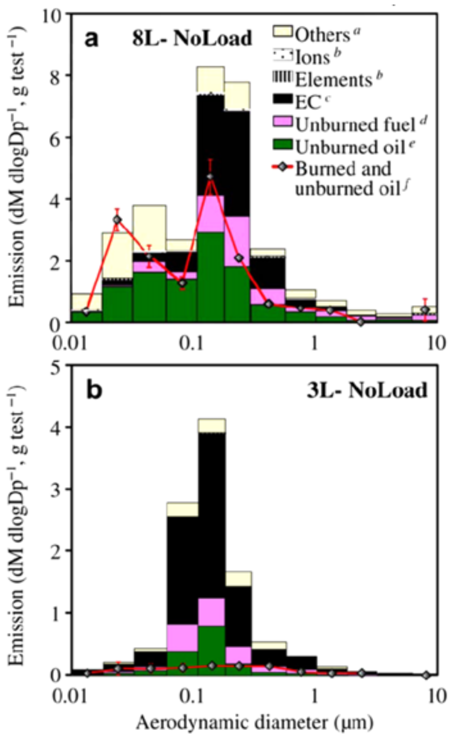

Figure 24. Oil consumption and particulate emissions by source, as estimated by using marker compounds: (a) nanoparticle-dominated condition (8 L-No Load), (b) accumulation-modedominated condition (3 L-No Load). [a]caculated by subtracting the sum of measured components from the particle mass; [b,c]measured values; [d]estimated by subtracting the unburned oil from measured OC × 1.17; [e]estimated from the 17α(H),21β(H)-hopane concentrations, with correction for oil evaporation; [f]plots show average estimates based on Ca and Zn.

emissions. An 8.0 L diesel engine with no after-treatment system and a 3.0 L diesel vehicle with a DOC were tested under no load conditions. Conventional 10W-30 oil and ULSD fuel (with 8 ppm sulfur) was used. Figure 24 shows the correlation between the oil consumption and particle emission by source, as estimated by using marker compounds.

2.5. Vehicle Driving Modes on PM Emissions

The formation of nano-particle emissions is closely related to engine operating conditions, ambient temperatures, and vehicle driving patterns. Tighter PM regulations for both gasoline and diesel vehicles will be set in the Euro 6 and the California LEV III emissions standards. Many studies have shown that traditional emissions certification modes do not represent real-world vehicles emissions performance. Thus, a substantial increase in regulated and non-regulated emissions have been reported from in-use vehicles during cold and hot ambient driving conditions, which aggravate the air quality in roadside and vehicle-congested areas (Johnson *et al*., 2011; Kirchner *et al*., 2013; Mock *et al*., 2013; Myung *et al*., 2013, 2014; Rakopoulos and Giakoumis, 2009).

The discrepancies between type-approval and real-world vehicle emissions can be complemented by adopting more realistic vehicle driving cycles that reflect aggressive driving (US06), air conditioning operation (SC03), and cold-FTP (-7°C) in the supplemental federal test procedure (SFTP) and the WLTC driving cycle. In response to the adoption of new test modes, engine and vehicle manufacturers have developed more sophisticated engine control strategies, high performance exhaust after-treatment technologies, and advanced powertrains (Johnson *et al*., 2011; Mamakos *et al*., 2013b; Weiss *et al*., 2012).

Real driving emission (RDE) testing with PEMS is another effective measure, which has procedures that cover a wide range of real-world vehicle driving conditions.

Recent researches have shown that a meaningful correlation between the PMP PN regulation method using CVS and PN-PEMS was observed for internal combustion engines for emission certification modes and real-world driving conditions (Kousoulidou *et al*., 2013)

However, there are additional challenges in measuring the PN with a PEMS that covers a wide range of vehicle operating conditions, such as ambient temperatures, detection limits, coefficient of variances (CoVs), instrument calibration, and the extra weight associated with a package solution (Kirchner *et al*., 2013). Figure 25 shows the fit to the PN measured with a PN-PEMS in a tailpipe and a CVS-chassis dynamometer.

Figure 26 shows the effect of vehicle driving cycles on the PN concentration, the particle size, and the number concentration for a 1.6 L stoichiometric SIDI passenger vehicle. The test modes are the NEDC, WLTC, and ARTEMIS cycles. The PN concentration for each cycle obtained using the PMP measurement procedure show that

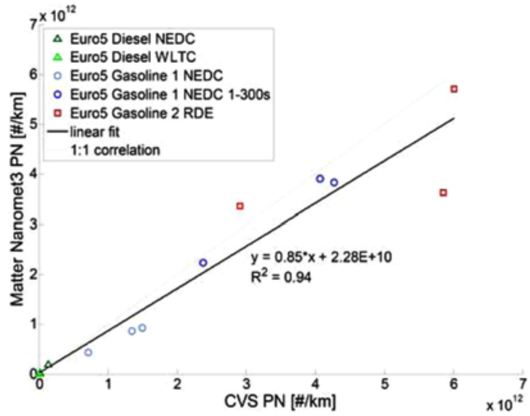

Figure 25. Linear fit of PN measured with the NanoMet3 PN-PEMS and using the regulatory method with a CVS dilution tunnel.

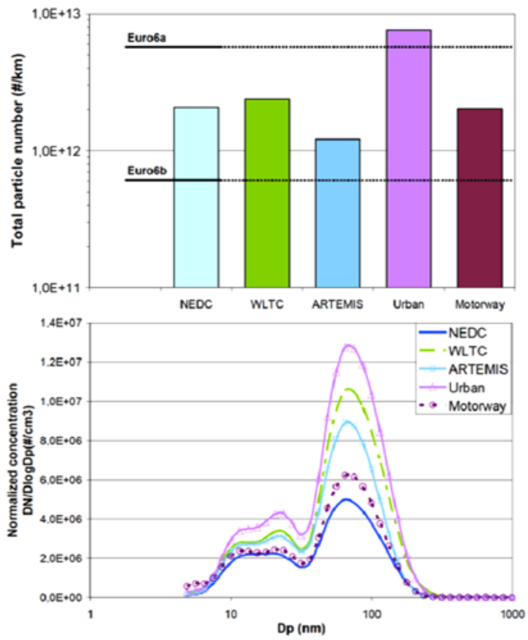

Figure 26. Effect of vehicle driving cycles on PN concentration, particle size, and number concentration for a 1.6 L stoichiometric SIDI passenger vehicle.

the vehicle does not meet the future Euro 6b limit. Compared to motorway conditions of the ARTEMIS cycle, the urban driving phase with a low load and low- speed transient conditions results in high PN emissions. Size-resolved PN emissions measured using a DMS500 in the tailpipe show that high concentrations of accumulation mode particles are generated under urban driving conditions (Noël *et al*., 2013).

The correlations between ambient temperatures and particle emissions characteristics from Euro 5 compliant vehicles show that PM and PN emissions substantially

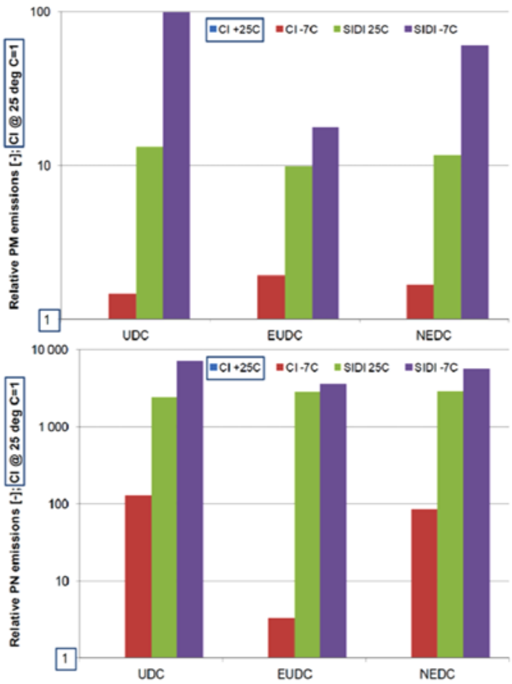

Figure 27. Relative PM and PN emissions from CI and GDI vehicles at test temperatures (25ºC and -7ºC) for the NEDC and its two phases.

increase at sub-zero ambient temperature conditions over the NEDC cycle, as shown in Figure 27. Two types of passenger vehicles with similar engine displacements and vehicle weights have been evaluated: a CI vehicle with a DOC-DPF and SIDI vehicles with a TWC. The results show that the PM emissions from the SIDI vehicles are much higher than those from the DPF-equipped CI vehicles, whereas the SIDI PN concentrations are orders of magnitude higher. The particle mass and the size-resolved PN emissions from the GDI vehicle are highly affected by the ambient temperature of -7ºC compared to the DPF CI vehicle because of the cold start and the warm transient effect (Bielaczyc *et al*., 2013; Dardiotis *et al*., 2013). Considering the particulate emission levels under real-world driving conditions from SIDI vehicles, installation of a GPF with TWC systems should be considered.

3. CONCLUSION

Many scientific studies and medical investigations have shown that PM emissions from internal combustion engines, especially ultrafine particles under 100 nm in size, adversely impact human health, resulting in heart and lung disease, cancer, and premature death. Implementing the stringent emission regulations of Euro 6 and LEV III will contribute to substantial reduction of particle mass and particle number emissions from new registered vehicles and engines. A CRDI diesel engine equipped with a DOC-DPF system was shown to significantly reduce both mass and number emissions simultaneously. PM emissions emitted from GDI engines are comparable to those from non-DPF diesel engines; thus, PM reduction technologies, i.e., engine control schemes, fuel injection strategies, combustion and air handling systems, and GPFs, are being intensively studied. In addition, implementing these technologies will effectively improve off-cycle emissions from real-world vehicles running at sub-zero ambient temperature, aggressive accelerations, and with air conditioning.

Particles from internal combustion engines are a complex mixture of volatile and non-volatile materials. The characterization of the physical and chemical PM fractions is strongly affected by fuels and engine oils specifications, engine operating conditions, ambient temperatures, and exhaust after-treatment systems. Soot particles and ash components are coated with various additive compounds and toxic compounds, such as cancer-causing aldehydes and PAHs. Engine oil with higher viscosities and lower volatilities can reduce both oil consumption and oil-oriented particulate emissions. The lubricant formulation of SAPS should be optimized to maintain the durability performance of powertrains and exhaust after-treatment systems. Studies on soot surface nanostructure are critical, because soot reactivity and oxidation rates depend on the PM morphology and chemical compositions. Detailed PM characterization using standard sampling procedures and various analytic instruments can eventually reduce emissions under real-world engine operating conditions to improve urban air qualities and human health.

ACKNOWLEDGEMENT–This study was supported by Korea University Grant and BK21 plus.

REFERENCES

Albuquerque, P. C., Ávila, R. N., Zárante, P. H. and Sodré, J. R. (2011). Lubricating oil influence on exhaust hydrocarbon emissions from a gasoline fueled engine. *Tribology Int.*, **44**, 1796−1799.

Arsie, I., Iorio, S. D. and Vaccaro, S. (2013). Experimental investigation of the effects of AFR, spark advance and EGR on nanoparticle emissions in a PFI SI engine. *J. Aerosol Sci*., **64**, 1−10.

Barone, T., Storey, J. M., Youngquist, A. D. and Szybist, J. P. (2012). An analysis of direct-injection spark-ignition (DISI) soot morphology. *Atmos*. *Environ*., **49**, 268–294.

Basshuysen, R. (2009). *Gasoline Engine with Direct Injection – Processes, Systems, Development, and Potential*. 1st edn. Vieweg+Teubner. Wiesbaden.

Beatrice, C., Iorio, S. D., Guido, C. and Napolitano, P. (2012). Detailed characterization of particulate emissions of an automotive catalyzed DPF using actual regeneration strategies. *Experimental Thermal and Fluid*

Science, **39**, 45−53.

Berndorfer, A., Breuer, S., Piock, W. and Bacho, P. V. (2013). Diffusion combustion phenomena in GDI engines caused by injection process. *SAE Paper No*. 2013-01-0261.

Bielaczyc, P., Klimkiewicz, D., Pajdowski, P., Szczotka, A. and Woodburn, J. (2013). A quantitative comparison of the particulate matter emissions from two Euro 5 vehicles (direct injection petrol & diesel). *17th ETH Conf. Combustion Generated Nanoparticles.*

Borge, P. (2013). *Death by Diesel.* Engine Technology International. UK.

Brandenbergera, S., Mohra, M., Grobb, K. and Neukomb, H. P. (2005). Contribution of unburned lubricating oil and diesel fuel to particulate emission from passenger cars. *Atmos. Environ*., **39**, 6985−6994.

Brijesh, P. and Sreedhara, S. (2013). Exhaust emissions and its control methods in compression ignition engines: A review. *Int. J. Automotive Technology* **14**, **2**, 195−206.

Burtscher, H. (2005). Physical characterization of particulate emissions from diesel engines: A review. *J. Aerosol Sci*., **36**, 896−932.

Bzdek, B. R., Pennington, R. and Johnston, M. V. (2012). Single particle chemical analysis of ambient ultrafine aerosol: A review. *J. Aerosol Sci*., **52**, 109−120.

CARB (2010). Proposed amendments to California's low-emission vehicle regulations – Particulate matter mass, ultrafine solid particle number, and black carbon emissions. Preliminary Discussion Paper.

Carroll, J. L., Khalek, I. A., Smith, L. E., Fujita, E. and Zielinska, B. (2011). Collaborative lubricating oil study on emissions (CLOSE). NREL Report, NREL/SR-5400-52668.

Carvalho, M. J., Seidl, P. R., Belchior, C. R. and Sodré, J. R. (2010). Lubricant viscosity and viscosity improver additive effects on diesel fuel economy. *Tribology Int*., **43**, 2298−2302.

Choi, K., Kim, J., Myung, C. L., Lee, M., Kwon, S., Lee, Y. and Park, S. (2012). Effect of the mixture preparation on the nanoparticle characteristics of gasoline direct-injection vehicles. *J. Automobile Engineering* **226**, **11**, 1514−1524.

Choi, K., Kim, J., Ko, A., Myung, C. L., Park, S. and Lee, J. (2013). Size-resolved engine exhaust aerosol characteristics in a metal foam particulate filter for GDI light-duty vehicle. *J. Aerosol Sci*., **57**, 54−70.

Choi, S. and Min, K. (2013). Analysis of the combustion and emissions of a diesel engine in early-injection, partially-premixed charge compression ignition regimes. *J. Automobile Engineering* **227**, **7**, 939−950.

Dardiotis, C., Martini, G., Marotta, A. and Manfredi, U. (2013). Low-temperature cold-start gaseous emissions of late technology passenger cars. *Applied Energy*, **111**, 468−478.

Delphi (2013). Worldwide Emissions Standards. www.delphi.com

Denner, V. (2013). Shaping the future – Innovations for efficient mobility. *33rd Internationales Wiener Motorensymposium*.

Dong, L., Shu, G. and Liang, X. (2013). Effect of lubricating oil on the particle size distribution and total number concentration in a diesel engine. *Fuel Processing Technology*, **109**, 78−83.

Duchaussoy, Y., Covin, B., Boccadoro, Y., Meurisse, O., Mercier, J. P. and Levasseur, D. (2011). The new RENAULT 1.2 GDI turbocharged engine. *20th Aachen Colloquium*.

Eastwood, P. (2008). *Particulate Emissions from Vehicles*. John Wiley & Sons Ltd. UK.

Eiglmeier, C., Bauder, R., Fröhlich, A., Gabel, K., Helbig, J., Marckwardt, H. and Zülch, S. (2011). The new 3.0 litre V6 TDI engine with dual-stage turbocharging in the Audi A6 and A7. *20th Aachen Colloquium*.

Fan, Q., Bian, J., Lu, H., Li, L. and Deng, J. (2012). Effect of the fuel injection strategy on first-cycle firing and combustion characteristics during cold start in a TSDI gasoline engine. *Int. J. Automotive Technology* **13**, **4**, 523−531.

Fraidl, G., Hollerer, P., Kapus, P. and Vidmar, K. (2012). Particulate number for EU6+ challenges and solutions. *Advanced Emission Control Concepts for Gasoline Engines Conf.*

Fushimia, A., Saitoha, K., Fujitania, Y., Hasegawaa, S., Takahashid, K., Tanabea, K. and Kobayashia, S. (2011). Organic-rich nanoparticles (diameter: 10-30 nm) in diesel exhaust: Fuel and oil contribution based on chemical composition. *Atmos. Environ*., **45**, 6326−6336.

Gaddam, C. and Vander Wal, R. L. (2013). Physical and chemical characterization of SIDI engine particulates. *Combustion and Flame*, **160**, 2517−2528.

Giechaskiel, B., Mamakos, A., Andersson, J., Dilara, P., Martini, G., Schindler, W. and Bergmann, A. (2012). Measurement of automotive nonvolatile particle number emissions within the European legislative framework: A review. *Aerosol Science and Technology*, **46**, 719−749.

Giechaskiel, B., Maricq, M., Ntziachristos, L., Dardiotis, C., Wang, X., Axamnn, H., Bergmann, A. and Schindler, W. (2014). Review of motor vehicle particulate emissions sampling and measurement: From smoke and filter mass to particle number. *Aerosol Science and Technology*, **67**, 48−86.

Hassaneen, A. E., Samuel, S. and Whelan, I. (2011). Combustion instabilities and nanoparticles emission fluctuations in GDI spark ignition engine. *Int. J. Automotive Technology* **12**, **6**, 787−794.

Hoshino, K., Hirata, M., Kurihara, I. and Tekeshima, S. (2005). Effects of engine oil composition on diesel particulate filter. *JSAE Paper No*. 20055128.

Hwang, I., Choi, K., Kim, J., Myung, C. L. and Park, S. (2012). Experimental evaluation of combustion phenomena in and nanoparticle emissions from a side-mounted direct-injection engine with gasoline and liquid-phase liquefied petroleum gas fuel. *J. Automobile Engineering* **226**, **1**, 112–122.

Inagaki, H. and Kondo, T. (2009). Influences of lubricating oil consumption on PM emission in gasoline engine. *JSAE Paper No*. 20095284.

Johnson, K. C., Thomas, D., Durbin, T. G., Jung, H. Cocker, D. R., Bishnu, D. and Giannelli, R. (2011). Quantifying in-use PM measurements for heavy duty diesel vehicles. *Environ. Sci. Technol*., **45**, 6073–6079.

Jung, H., Kittelson, D. B. and Zachariah, M. R. (2003). The influence of engine lubricating oil on diesel nanoparticle emissions and kinetics of oxidation. *SAE Paper No*. 2003-01-3170.

Kern, B., Spiess, S. and Richter, J. M. (2013). The challenge of emission legislation EU6c for gasoline-DI-engines, strategies meeting the new demands and preparing for extended test conditions. *22nd Aachen Colloquium*.

Kim, H. J., Han, B., Cho, G. B., Kim, Y. J., Yoo, J. S. and Oda, T. (2013a) Collection performance of an electrostatic filtration system combined with a metallic flow-through filter for ultrafine diesel particulate matters. *Int. J. Automotive Technology* **14**, **3**, 489–497.

Kim, Y., Kim, Y. H., Jun, S. Y., Lee, K. H., Rew, S. H., Lee, D. and Park, S. (2013b). Strategies for particle emissions reduction from GDI engines. *SAE Paper No*. 2013-01-1556.

Kim, J., Choi, K., Myung, C. L. and Park. S. (2013c). Experimental evaluation of engine control strategy on the time resolved THC and nano-particle emission characteristics of liquid phase LPG direct injection (LPG-DI) engine during the cold start. *Fuel Processing Technology*, **106**, 166–173.

Kirchner, U., Gallus, J., Börensen, C. and Vogt, R. (2013). Particle number emission of light-duty vehicles during real-world driving. *17th ETH Conf. Combustion Generated Nanoparticles.*

Ko, A., Kim, J., Choi, K., Myung, C. L., Kwon, S., Kim, K., Cho, Y. J. and Park, S. (2012). Experimental study of particle emission characteristics of a heavy-duty diesel engine and effects of after-treatment systems: Selective catalytic reduction, diesel particulate filter, and diesel particulate and NOx reduction. *J. Automobile Engineering* **226**, **12**, 1689–1696.

Konstandopoulos, A. G. and Papaioannou, E. (2008). Update on the science and technology of diesel particulate filters. *KONA Powder and Particle*, **26**, 36–65.

Kousoulidou, M., Fontaras, G., Ntziachristos, L., Bonnel, P., Samaras, Z. and Dilara, P. (2013). Use of portable emissions measurement system (PEMS) for the development and validation of passenger car emission factors. *Atmos. Environ*., **64**, 329–338.

Kufferath, A., Berns, S., Hammer, J., Busch, R., Frank, M. and Storch, A. (2012). The EU6 challenge at GDI – Assessment of feasible system solutions. *33rd Internationales Wiener Motorensymposium*.

La Rocca, A., Shayler, P. J. and Fay, M. W. (2013). Nanoparticle characteristics of exhaust and soot-in-oil from a light duty diesel engine. *17th ETH Conf. Combustion Generated Nanoparticles.*

Lee, S., Cho, Y., Song, M., Kim, H., Park, J. and Baik, D. (2012). Experimental study on the characteristics of nano-particle emissions from a heavy-duty diesel engine using a Urea-SCR system. *Int. J. Automotive Technology* **13**, **3**, 355–363.

Lee, D., Choi, S. C. and Lee, C. S. (2013a). Impact of SME blended fuel combustion on soot morphological characteristics in a diesel engine. *Int. J. Automotive Technology* **14**, **5**, 757–762.

Lee, J., Choi, S., Kim, H., Kim, D., Choi, H. and Min, K. (2013b). Reduction of emissions with propane addition to a diesel engine. *Int. J. Automotive Technology* **14**, **4**, 551–558.

Lee, J., Hong, K., Choi, S., Yu, S., Choi, H. and Min, K. (2013c). Comparison of the effects of multiple injection strategy on the emissions between moderate and heavy EGR rate conditions: Part 1-pilot injections. *J. Mechanical Science and Technology* **27**, **4**, 1135–1141.

Liati, A. and Eggenschwiler, P. D. (2010). Characterization of particulate matter deposited in diesel particulate filters: Visual and analytical approach in macro-, micro- and nano-scales. *Combustion and Flame*, **157**, 1658–1670.

Liati, A., Eggenschwiler, P. D., Gubler, E. M., Schreiber, D. and Aguirre, M. (2012). Investigation of diesel ash particulate matter: A scanning electron microscope and transmission electron microscope study. *Atmos. Environ*., **49**, 391–402.

Lu, T., Huang, Z., Cheng, C. S. and Ma, J. (2012). Size distribution of EC, OC and particle-phase PAHs emissions from a diesel engine fueled with three fuels. *Science of the Total Environment*, **438**, 33–41.

Mamakos, A., Martini, G., Dilara, P. and Drossinos, Y. (2011). Feasibility of Introducing Particulate Filters on Gasoline Direct Injection Vehicles. JRC Report, EUR 25297 EN.

Mamakos, A., Bonnel, P., Perujo, A. and Carriero, M. (2013a). Assessment of portable emission measurement systems (PEMS) for heavy-duty diesel engines with respect to particulate matter. *J. Aerosol Sci*., **57**, 54–70.

Mamakos, A., Martini, G. and Manfredi, U. (2013b). Assessment of the legislated particle number measurement procedure for a Euro 5 and a Euro 6 compliant diesel passenger cars under regulated and unregulated conditions. *J. Aerosol Sci*., **55**, 31–47.

Maricq, M. M. (2007). Chemical characterization of particulate emissions from diesel engines: A review. *J. Aerosol Sci.*, **38**, 1079–1118.

Mock, P., German, J., Bandivadekar, A., Riemersma, I., Ligterink, N. and Lambrecht, U. (2013). A comparison of official and 'real-world' fuel consumption and CO_2

values for cars in Europe and the United States. ICCT, White Paper.

Momenimovahed, A., Olfert, J. S., Checkel, M. D., Pathak, S., Sood, V., Robindro, L., Singal, K., Jain, A. K. and Garg, O. (2013). Effect of fuel choice on nanoparticle emission factors in LPG-gasoline bi-fuel vehicles. *Int. J. Automotive Technology* **14**, **1**, 111.

Myung, C. L., Choi, K., Kim, J., Lim, Y., Lee, J. and Park, S (2012a). Comparative study of regulated and unregulated toxic emissions characteristics from a spark ignition direct injection light-duty vehicle fueled with gasoline and liquid phase LPG (liquefied petroleum gas). *Energy*, **44**, 189−196.

Myung, C. L., Kim, J., Choi, K., Hwang, I. and Park, S. (2012b). Comparative study of engine control strategies for particulate emissions from direct injection light-duty vehicle fueled with gasoline and liquid phase liquefied petroleum gas (LPG). *Fuel*, **94**, 348−355.

Myung, C. L., Ko, A., Kim, J., Choi, K., Kwon, S. and Park, S. (2013). Specific engine performance and gaseous emissions characteristics of European test cycle and worldwide harmonized driving cycle for a heavy-duty diesel engine. *J. Mechanical Science and Technology* **27**, **12**, 3893−3902.

Myung, C. L., Ko, A., Lim, Y., Kim, S., Lee, J., Choi, K. and Park, S. (2014). Mobile source air toxic emissions from direct injection spark ignition gasoline and LPG passenger car under various in-use vehicle driving modes in Korea. *Fuel Processing Technology*, **119**, 19−31.

Myung, C. L. and Park, S. (2012). Exhaust nanoparticle emissions from internal combustion engines: A review. *Int. J. Automotive Technology* **13**, **1**, 9−22.

Neußer, H. J., Kahrstedt, J., Jelden, H., Dorenkamp, R. and Düsterdiek, T. (2013). The EU6 engines based on the modular diesel system of Volkswagen-Innovative exhaust gas purification near the engine for further minimization of NOx and CO_2. *34th Internationales Wiener Motorensymposium*.

Noël, L., Hayrault, P., Leblanc, M., Raux, S. and Jeuland, N. (2013). Detailed characterization of nanoparticles emitted by spark ignition direct injection engines. *17th ETH Conf. Combustion Generated Nanoparticles.*

Ntziachristos, L., Fragkiadoulakis, P., Samaras, Z., Janka, K. and Tikkanen, J. (2011). Exhaust particle sensor for OBD application. *SAE Paper No*. 2011-01-0626.

Ohm, I. Y. (2013). Effects of intake valve angle on combustion characteristic in an SI engine. *Int. J. Automotive Technology* **14**, **4**, 529−537.

Omae, K., Tomoda, T., Hashimoto, H., Matsumoto, S., Tanaka, A. and Uchiyama, K. (2012). Innovative fuel injection system for future Toyota diesel passenger cars. *33rd Internationales Wiener Motorensymposium*.

Opitza, B., Drochner, A., Vogelb, H. and Votsmeiera, M. (2013). An experimental and simulation study on the cold start behaviour of particulate filters with wall integrated three way catalyst. *Applied Catalysis B: Environmental*, **144**, 203−215.

Paul, B., Datta, A. and Sahab, A. (2013). Optical characterization of nano-sized organic carbon particles emitted from a small gasoline engine. *Particuology*, **11**, 249−255.

Rahman, S. M., Masjuki, H. H., Kalam, M. A., Abedin, M. J., Sanjid, A. and Sajjad, H. (2013). Impact of idling on fuel consumption and exhaust emissions and available idle-reduction technologies for diesel vehicles – A review. *Energy Conversion and Management*, **74**, 171−182.

Rakopoulos, C. and Giakoumis, E. (2009). *Diesel Engine Transient Operation - Principles of Operation and Simulation Analysis*. Springer. UK.

Richter, J. M., Klingmann, R., Spiess, S. and Wong, K. F. (2012). Application of catalyzed gasoline particulate filters to GDI vehicles. *SAE Paper No*. 2012-01-1244.

Sakono, T., Nakai, E., Kataoka, M., Takamatsu, H. and Terazawa, Y. (2011). Mazda SKYACTIV-D 2.2L diesel engine. *20th Aachen Colloquium*.

Sanchez, F. P., Bandivadekar, A. and German, J. (2012). Estimated cost of emission reduction technologies for light-duty vehicles. ICCT.

Sappok, A., Morrow, R., Wong, V., Pazar, J., Doustar, I. and Zisholtz, E. (2010). Unraveling DPF degradation using chemical tracers and opportunities for extending filter life. *DEER Conf.*

Schöppe, D., Zhang, H., Rösel, G., Achleitner, E., Kapphan, F. and Dupont, H. (2013). Next generation engine management systems for gasoline direct injection. *34th Internationales Wiener Motorensymposium*.

Shim, B. J., Park, K. S., Koo, J. M., Nguyen, M. S. and Jin, S. H. (2013). Estimation of soot oxidation rate in DPF under carbon and non-carbon based particulate matter accumulated condition. *Int. J. Automotive Technology* **14**, **2**, 207−212.

Stetter, J., Forster, N., Ghandhi, J. and Foster, D. (2003) The impact of oil consumption mechanisms on diesel exhaust particle size distributions and detailed exhaust chemical composition. *DEER Conf.*

Thiruvengadam, A., Besch, M., Carder D., Oshinuga, A. and Gautam, M. (2012). Influence of real-world engine load conditions on nanoparticle emissions from a DPF and SCR equipped heavy-duty diesel engine. *Environ. Sci. Technol.*, **46**, 1907−1913.

Vincent, J. H. (2007). *Aerosol Sampling – Sciences, Standards, Instrumentations, and Applications*. John Wiley & Sons Ltd. UK.

Weiss, M., Bonnel, P., Kühlwein, J., Provenza, A., Lambrecht, U., Alessandrini, S., Carriero, M., Colombo, R., Forni, P., Lanappe, G., Lijour, P. L., Manfredi, U., Montigny, F. and Sculati, M. (2012). Will Euro 6 reduce the NOx emissions of new diesel cars? - Insights from on-road tests with portable emissions measurement systems (PEMS). *Atmos. Environ.*, **62**, 657−665.

Whitaker, P., Kapus, P., Ogris, M. and Hollerer, P. (2011).

Measures to reduce particulate emissions from gasoline DI engines. *SAE Paper No*. 2011-01-1219.

Wang, D., Liu, Z. C., Tian, J., Liu, J. W. and Zhang, J. R. (2012). Investigation of particle emission characteristics from a diesel engine with a diesel particulate filter for alternative fuels. *Int. J. Automotive Technology* **13**, **7**, 1023−1032.

Wang, L., Song, C., Song, J., Lv, K., Pang, H. and Zhang, W. (2013). Aliphatic C–H and oxygenated surface functional groups of diesel in-cylinder soot: Characterizations and impact on soot oxidation behavior. *Proc. Combustion Institute*, **34**, 3099−3106.

Yamano, J., Ikoma, K., Matsui, R., Ikegami, N., Mori, S. and Yano, T. (2013). The new "Earth Dreams Technology i-DTEC" 1.6 L diesel engine from Honda. *34th Internationales Wiener Motorensymposium*.

Zhang, S. and McMahon, W. (2012). Particulate emissions for LEV II light-duty gasoline direct injection vehicles. *SAE Paper No*. 2012-01-0442.

Zhao, H. (2010). *Advanced Direct Injection Combustion Engine Technologies and Development – Volume 2: Diesel Engines*. Woodhead Publishing Limited. UK.