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Correlations between particulate matter emissions and gasoline direct injection spray characteristics

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ABSTRACT

The present work investigates impacts of fuel delivery system on Particulate Matter (PM) emissions in a latest generation gasoline Direct Injection Spark Ignition (DISI) engine. Particulate number concentration and size distribution were studied over a wide size range for homogeneous and heterogeneous in-cylinder fuel/air mixtures at different engine speeds/loads. Various fuel spray angles and fuel flow rates were employed to investigate effects of fuel wetting and mixture preparation on particulate emissions. Experimental results highlighted intricate relation between particulate formation/oxidation and engine operating parameters that dictates optimum spray characteristics for lowest PM emissions. The study revealed fuel impingement on hot piston surface during early injection timings and consequent fuel pyrolysis and diffusion flame result in PM size distributions with a peak in accumulation mode (particle diameter ≥50 nm). On the other hand, late fuel impingement on cylinder liner and insufficient time for mixture preparation, result in PM size distributions with a peak around 10-15 nm in nucleation mode. It was concluded that for the latter case, condensation of unburned hydrocarbons was more significant than adsorption into exiting particles' surface.

1. Introduction

Current powertrain development trends indicate spark ignition engines remain as one of the most dominant power unit types for passenger cars for the coming years. Although, gasoline Port Fuel Injection (PFI) engines are the most common engine type, global production volume of Direct Injection Spark Ignition (DISI) engines will overtake that of the PFI engines. The DISI technologies can improve engine efficiency and performance while reduce gaseous emissions. Albeit, control of Particulate Matter (PM) emissions of the DISI engines is a challenge. Even though DISI engines emit relatively low PM emissions by mass compared to diesel engines, they emit substantial amounts of ultrafine particles. Therefore, Particulate matter Number (PN) concentration and morphology are more relevant metrics than the total PM mass for DISI engines. These particles cover a variety of sizes and are often divided into three size classes: nucleation mode (diameter (d) $\leq 50nm$), accumulation mode (50nm$<d<$1μm) and coarse mode ($d \geq$ 1 μm). The chemical compositions of gasoline exhaust PM emissions of PFI and DI engines are well known (Andersson, Wedekind, Hall, & Stradling, 2001; Bosteels, May, Karlsson, & de Serves, 2006; Fushimi et al., 2016; Khalek, Bougher, & Jetter, 2010; Mohr, Lehmann, & Margaria, 2003; Schauer, Christensen, Kittelson, Johnson, & Watts, 2008). These particles are generated from four different sources: fuel, lubricant, air and material breakdown. They are composed of different volatile and non-volatile compositions including organic (such as alcohols, aromatics), sulphate (sulphuric acid), nitrate (nitric acid), ash (metals and non-metals) and

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Nomenclature

AED	aerodynamic equivalent diameter
ATDC	after top dead center
BTDC	before top dead center
CAD	crank angle degree
COV	coefficient of variation
CPC	condensation particle counter
CS	catalytic stripper
CVVL	continuous variable valve lift
DISI	direct injection spark ignition
DMS	differential mobility spectrometer
ECU	engine control unit
FIE	fuel injection equipment
FTP	federal test procedure
GDI	gasoline direct injection
MFB	mass fraction burned
NEDC	new European driving cycle
NMEP	net mean effective pressure
NSFC	net specific fuel consumption
PEMS	portable emissions measurement system
PFI	port fuel injection
PM	particulate matter
PMP	particle measurement program
PN	particulate matter number
PSD	particle size distribution
RDE	real driving emissions
SOI	start of injection
TD	thermal denuder
TDC	top dead center
ULG	unleaded gasoline
VCT	variable camshaft timing
VCU	valve control unit
VPR	volatile particle remover
WLTC	world harmonized light duty test cycle

carbonaceous (mainly soot). Soot as the main component simultaneously form, grow (including: surface grow, coagulation and aggregation) and oxidize during combustion and exhaust process. Soot particles formation from fuel arises from fuel molecules oxidation and pyrolysis which lead to generation of large number of very small (d < 2 nm) soot precursors. Carbon/oxygen ratio has been used to define composition of the fuel-oxidizer mixture at onset of soot formation in flames. From equilibrium considerations, soot formation occurs when carbon/oxygen ratio exceeds unity (Haynes & Wagner, 1981). Hence, in

$$C_mH_n+yO_2\rightarrow 2_yCO+\frac{n}{2}H_2+(m-2y)C \tag{1}$$

when 'm' becomes larger than '2y'. The corresponding fuel/air equivalence ratio is given by

$$\phi=2\left(\frac{C}{O}\right)(1+\delta) \tag{2}$$

where $\delta = n/(4m)$. Reported in several studies, soot formation typically occurs under locally rich (ϕ > 1.4) and hot conditions with local temperatures from around 1100 to 1700 °C, whereas, soot oxidation is most efficient under stoichiometric to lean conditions, and at temperatures above 1700 °C (Dec, 1997; Graskow, Kittelson, Abdul-Khalek, & Ahmadi, 1998; Kittelson, 1998). It is believed that the chemistry involved in soot formation has same character in both premixed flame (in spark ignition engines) and diffusion flame (in compression ignition engines). However, soot precursor formation through fuel oxidation and pyrolysis in premixed flames is competing with oxidative attack on these precursors, while in diffusion flames no such attack occurs on precursors (Glassman & Yetter, 2008). Eventual engine-out soot emission is a balance between the two (soot formation and soot oxidation). Additionally, hydrocarbons in the exhaust gases and atmosphere affect engine-out soot through adsorption into the soot particle surface and condensation to form new particles of hydrocarbon species (Amanna & Sieglaa, 1981).

Numerous medical studies have linked particulates exposure to health problems. Some researchers subdivide particles based on their Aerodynamic Equivalent Diameter (AED) which defines where they deposit in human body. Three AED fractions of < 10, < 2.5, and < 0.1 µm (PM10, PM2.5, and PM0.1, respectively) are typically used. The World Health Organization estimated that PM2.5 concentration contributes to approximately 800,000 premature deaths per year and ranked it as the 13th leading cause of mortality worldwide (World health report, 2002). Several studies evaluated PM exposure on cardiovascular (Brook et al., 2010; Forbes, Patel, Rudnicka, Cook, & Bush, 2009; Hoffmann, Moebus, Dragano, Stang, & Möhlenkamp, 2009; Pope, Burnett, Thurston, Thun, & Calle, 2004; Rückerl, Ibald-Mulli, Koenig, Schneider, & Woelke, 2006; Sullivan, Hubbard, Liu, Shepherd, & Trenga, 2007), respiratory (Behndig, Mudway, Brown, Stenfors, & Helleday, 2006; Desqueyroux, Pujet, Prosper, Squinzai, & Momas, 2002; Gent, Koutrakis, Belanger, Triche, & Holford, 2009; Goss, Newsom, Scholdcrout, Sheppard, & Kaufman, 2004; Hogg, Chu, Utokaparch, Woods, & Elliott, 2004) and cerebrovascular health effects (Henrotin, Besancenot, Bejot, & Giroud, 2007; O'Donnel, Fang, Mittleman, Kapral, & Wellenius, 2011; Wellenius, Schwartz, & Mittleman, 2005). In addition, some of identified effects of PM on environment include: reduced visibility, increased acidity of lakes and streams, reduced level of nutrients in soil, reduced diversity in ecosystems, damage to stone and other materials (Bond et al., 2013; United States Environmental Protection Agency, 2014). With increasing concern over air quality and human health, regulations for engines' particulate mass were introduced in various countries. However, only the European Commission introduced regulations for DISI engines particulate number (EC, 2012). This was initiated as a number of studies on the emission performance of DISI engines showed that while they can easily comply with the PM mass limit, their PN emissions consistently exceed the diesel threshold (e.g. see Mamakos, Dardiotis, & Martini, 2011). Stricter PM legislations in Europe come with change in test cycle from current NEDC (New European Driving Cycle) to new World Harmonized Light Duty Test Cycle (WLTC) which will be used for vehicles certifications. In addition, Real Driving Emissions (RDE) will be implemented into the legislations and Portable Emissions Measurement Systems [PEMS] will be employed. This means particulate