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Experimental investigation of the effect of inlet particle properties on the capture efficiency in an exhaust particulate filter

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ABSTRACT

The impact of inlet particle properties on the filtration performance of clean and particulate matter (PM) laden cordierite filter samples was evaluated using PM generated by a spark-ignition direct-injection (SIDI) engine fuelled with tier II EEE certification gasoline. Prior to the filtration experiments, an advanced aerosol characterization system that comprised of a scanning mobility particle spectrometer (SMPS), centrifugal particle mass analyzer (CPMA), a differential mobility analyzer (DMA), and a single particle mass spectrometer (SPLAT II) was used to obtain a wide range of information on the SIDI PM emissions including particle size distribution (PSD), composition, mass, and dynamic shape factors (DSFs) in the transition (χ_t) and free-molecular (χ_v) flow regimes. During the filtration experiments, real-time measurements of PSDs upstream and downstream of the filter sample were used to estimate the filtration performance and the total trapped mass within the filter using an integrated particle size distribution method. The filter loading process was paused multiple times to evaluate the filtration performance in the partially loaded state. The change in vacuum aerodynamic diameter (d_{va}) distribution of mass-selected particles was examined for flow through the filter to identify whether preferential capture of particles of certain shapes occurred in the filter. The filter was also probed using different inlet PSDs. Pausing the filter loading process and subsequently performing the filter probing experiments did not impact the overall evolution of filtration performance. Within the present distribution of particle sizes, filter efficiency was independent of particle shape potentially due to the diffusion-dominant filtration process. Particle mobility diameter and trapped mass within the filter appeared to be the dominant parameters that impacted filter performance.

1. Introduction

The stratified nature of combustion in modern spark-ignition direct-injection (SIDI) engines, combined with wetting of piston and wall surfaces, results in a significant increase in emission of nanoparticles from SIDI engines compared to traditional port fuel-

Abbreviations: APM, Aerosol particle mass analyzer; CAD, Crank angle degrees; CPC, Condensation particle counter; CPMA, Centrifugal particle mass analyzer; CT, Computerized tomography; DMA, Differential mobility analyzer; DSF, Dynamic shape factor; EEPS, Engine exhaust particle spectrometer; EFA, Exhaust filtration analysis system; EOI, End of injection timing; EPA, Environmental protection agency; FE, Filtration efficiency (%); FV, Filtration velocity (cm/s); FWHM, Full-width at half-maximum; GCI, Gasoline compression ignition; HL, Heavy load engine operation; IPSD, Integrated particle size distribution method; MBT, Maximum brake torque; MPPS, Most penetrating particle size (nm); PFD, Partial flow diluter; PM, Particulate matter; PSD, Particle size distribution; SIDI, Spark-ignited direct-injection; SMPS, Scanning mobility particle spectrometer; SPLAT, Single-particle laser-ablation time-of-flight mass spectrometer

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Nomenclature

D_f	Fractal dimension	v_s	Superficial velocity (cm/s)
D_{fm}	Fractal dimension from mass-mobility data	ρ_0	Unit material density ($1000 kg/m^3$)
d_R	Interception equivalent diameter (nm)	ρ_{eff}	Effective density (g/cm^3)
d_a	Aerodynamic diameter (nm)	ρ_p	Particle density (g/cm^3)
d_m	Mobility diameter (nm)	χ_t	Dynamic shape factor in transition flow regime
d_{va}	Vacuum aerodynamic diameter (nm)	χ_v	Dynamic shape factor in free-molecular flow regime
d_{ve}	Volume equivalent diameter (nm)	Δp	Pressure drop (kPa)
m_p	Particle mass (fg)	M'''	IPSD mass concentration (g/cm^3)
n_{d_m}	Size-resolved number concentration ($1/cm^3$)	k	Permeability (m^2)

injected gasoline engines (Chan et al., 2012; Hall & Dickens, 1999; Stojkovic, Fansler, Drake, & Sick, 2005; Zhao, Lai, & Harrington, 1999). The harmful nature of these nanoparticle emissions (Ibald-Mulli, Wichmann, Kreyling, & Peters, 2002; Peters, Wichmann, Tuch, Heinrich, & Heyder, 1997; Valavanidis, Fiotakis, & Vlachogianni, 2008) has led to number-based emissions regulations for particulate matter (PM) from SIDI engines in the European Union since 2014, with more stringent regulations going into effect in 2017. Particle number (PN)-based regulations for gasoline vehicles have been proposed in other parts of the world following Europe's lead. India will be implementing Euro 6 PN requirements for gasoline vehicles in 2020, while the fuel-neutral China 6 PN-based standards will go into effect in 2019. Gasoline particulate filters (GPF) have been demonstrated to be effective means of reducing tailpipe PM mass and number emissions (Johnson, 2013; Mamakos, Martini, Marotta, & Manfredi, 2013), but large gaps in the fundamental understanding of filtration in GPFs exists.

Typically, exhaust particulate filters for gasoline and diesel engine applications are exposed to PM with sizes ranging from a few nanometers to micron-sized particles, depending on the engine operating conditions. The majority of these particles are fractal soot agglomerates comprised of primary spherules (Park, Cao, Kittelson, & McMurry, 2002). For the range of particle sizes trapped by automotive exhaust filters, diffusion and interception have been shown to be the dominant capture mechanisms (Konstandopoulos & Johnson, 1989; Viswanathan et al., 2015). The net capture efficiency by these mechanisms is commonly associated with dimensionless parameters that are dependent on both the particle morphology and filter structure (Hinds, 1999). The length scales associated with filtration can span multiple orders of magnitude based on the clean filter properties and the evolution of filter structure due to trapped PM. The current study focuses on understanding the impact of inlet particle properties on capture efficiency within an exhaust particulate filter under different levels of PM loading in the filter wall. To the best of the authors' knowledge, this is the first study attempting to isolate the impact of the combustion generated particle morphology (shape and size) on filtration capture efficiency in clean and partially loaded ceramic particulate filters.

2. Background

Particle morphology plays an important role in determining a particle's behavior in a filter medium. The complex nature of agglomerated PM requires multiple parameters to effectively define their morphology and behavior. For instance, different equivalent diameters, particle electrical mobility (d_m), aerodynamic (d_a), and vacuum aerodynamic (d_{va}) diameters, are used to describe particle behavior in different flow regimes under the influence of various forces (DeCarlo, Slowik, Worsnop, Davidovits, & Jimenez, 2004; Zelenyuk, Cai, & Imre, 2006). To account for the fact that the behavior of an aspherical particle depends on its shape, a correction factor known as a dynamic shape factor (DSF or χ) is used. The DSF is defined as the ratio of the drag force on an aspherical particle to the drag on a sphere of the same volume-equivalent diameter (d_{ve}) moving with the same velocity. The volume equivalent diameter is the diameter that the particle would have if it were melted to form a droplet while preserving any internal void spaces (DeCarlo et al., 2004). Note that DSF is not an intrinsic particle property but a measure of its behavior. The DSF depends on gas pressure and particle size, hence on the flow regime, and particle orientation. Here, we use DSFs in the transition (χ_t) and free molecular (χ_v) flow regimes to characterize particle shapes.

Zelenyuk et al. (2014) utilized different sequential combinations of an aerosol particle mass analyzer (APM) (or centrifugal particle mass analyzer (CPMA)), a differential mobility analyzer (DMA), and a single particle mass spectrometer (SPLAT II) to extensively characterize PM emissions from a gasoline compression ignition (GCI) engine operated under different load conditions. Direct simultaneous measurements of m_p, d_m, d_{va}, and composition of GCI exhaust particles were subsequently used to calculate several other particle properties, including particle density (ρ_p), mass-mobility power-law exponent (D_{fm}), d_{va}-d_m fractal dimension, χ_v, χ_t, average primary spherule diameter, number of primary spherules for a given particle mass, and void fraction (Shapiro et al., 2012; Zelenyuk et al., 2014). Moreover, Beranek, Imre, and Zelenyuk (2012) demonstrated that by combining all three instruments (APM/DMA/SPLAT system), it is possible to select and characterize particles with *one charge* and a narrow distribution of mass and mobility, and thus, shapes. The impact of multiply charged particles was also discussed in significant detail and was demonstrated to be insignificant while using the combined system. The information obtained using these advanced characterization techniques, enables the fundamental filtration experiments discussed in this paper focused on understanding the relative importance of morphological parameters on the capture efficiency of agglomerated particles within a filter.

Despite the fractal nature of combustion generated PM, many filtration models operate under the assumption of spherical particle morphology to evaluate the impact of different capture mechanisms. This can lead to inherent errors in estimation of capture