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Effective density of airborne wear particles from car brake materials

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A B S T R A C T

People living in urban environments are subject to high health risks due to various anthropogenic sources of airborne particulate matter, including wear of transport vehicle brakes. Studies of airborne particles often require an estimate of the effective particle density, a property that allows correct matching of mass and size characteristics measured by different aerosol instruments. In this study we investigated the effective density of airborne wear particles emitted from car brake materials. The particles were generated by a pin-on-disc machine located in a sealed chamber. Two methods were used to determine the effective density. The first method is based on measurements of PM10 and particle size distribution. The second method involves measurements and subsequent fitting of the mobility size distribution and aerodynamic size distribution. Results from the two methods showed good agreement. It was found that the effective density is $0.75 \pm 0.2\ g/cm^3$. The particle emission, size distribution and effective density are sensitive to temperature variations. An intensive emission of ultrafine particles is initiated at the disc temperature of $185 \pm 16\ ^\circ C$. The effective density decreases with the temperature in the interval 110–360 °C. There is a large difference between the effective density and the density of the particle material, which suggests that the particles are porous.

1. Introduction

Airborne particulate matter can be detrimental to human health. Particles penetrate the human body continuously through breathing, drinking, eating, and skin contact. Inhaled submicron particles reach the deepest parts of the lungs and enter the bloodstream (Oberdörster et al., 2005). Correlations were found between high concentrations of airborne particulate matter and increased morbidity due to various diseases (Gasser et al., 2009; Pope et al., 2002). People living in urban environments are subject to higher health risks due to airborne particles from various anthropogenic sources (Vu, Delgado-Saborit, & Harrison, 2015), including the burning of fossil fuels to generate electricity, construction, demolition, and transport vehicles. The latter has an especially significant influence in the vicinity of traffic arteries (Furusjö, Sternbeck, & Cousins, 2007; Pant & Harrison, 2013). The main sources of traffic-related particles are combustion of fuel in the engine, vehicle-caused turbulence, wear of the road surfaces, and wear of vehicle friction components (Amato et al., 2014; Gietl, Lawrence, Thorpe, & Harrison, 2010). Modern cars are equipped with disc brakes in which braking torque is provided by the friction of two pads against a disc. The disc is usually cast iron. Most of the pad materials fall into three classes: low-metallic (LM), non-asbestos organic (NAO), and semi-metallic (SM). During braking, wear particles are emitted from the friction surfaces of the pads and disc, and some of these particles become airborne and are released to the environment. Car brakes contribute considerably to traffic-related particulate matter (Hjortenkrans, Bergbäck, & Häggerud, 2007;

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Nomenclature

d	particle diameter, μm
d_a	aerodynamic diameter, μm
d_b	mobility diameter, μm
d_i	midpoint of the i-th stage, μm
i, j	index variables
$k_i(\bullet)$	kernel function of the i-th ELPI+ stage
m	particle mass concentration, μg/m^3
m_p	particle mass, g
n	number of the ELPI+ stages, $n=14$
p	contact pressure, MPa
v	sliding velocity, m/s
v_s	steady sliding velocity, m/s
C	particle concentration, no/cm^3
$C_c(\bullet)$	slip correction factor
$D(\bullet)$	particle mobility size distribution, no/(μm cm^3)
$E_i(\bullet)$	collection efficiency function of the i-th ELPI+ stage
$E_{ch}(\bullet)$	ELPI+ charger efficiency function, fA cm^3
I_i	electrical current at the i-th ELPI+ stage, fA
I_{si}	simulated electrical current at the i-th stage, fA
N_i	particle concentration at the i-th stage, no/cm^3
T	disc temperature, °C
T_s	stationary disc temperature, °C
T_u	critical temperature, °C
V_a	apparent particle volume, cm^3
V_i	volume of the i-th phase of the particle, cm^3
V_p	volume of the material in the particle, cm^3
V_v	volume of the void space in the particle, cm^3
ε	deviation of I_{si} from I_i
ρ	variable parameter (effective particle density), g/cm^3
ρ_0	unit density, $\rho_0=1$ g/cm^3
ρ_{e1}, ρ_{e2}	effective particle density (first and second definitions), g/cm^3
ρ_i	density of the i-th phase of the particle, g/cm^3
ρ_m	particle material density, g/cm^3
ρ_p	particle density, g/cm^3
ϕ	particle porosity
APM	aerosol particle mass analyser
APS	aerodynamic particle sizer
DMA	differential mobility analyser
ELPI	electrical low pressure impactor
FMPS	fast mobility particle sizer
LM	low-metallic material
MOUDI	micro-orifice uniform deposit impactor
NAO	non-asbestos organic material
OPS	optical particle sizer
PM10	mass concentration of particles smaller than 10 μm, μg/m^3
SM	semi-metallic material
SMPS	scanning mobility particle sizer
TEOM	tapered element oscillating microbalance

Thorpe & Harrison, 2008).

A number of studies have investigated car brake materials in relation to airborne wear particle emissions and associated ecological problems (Grigoratos & Martini, 2015). Garg, Cadle, Mulawa, and Groblicki (2000) studied particle emissions from brakes with NAO and SM pads using a brake dynamometer. The particle emission rate and aerodynamic size distribution were obtained using a Dekati electrical low pressure impactor (ELPI) with 0.03–10 μm aerodynamic diameter range, an MSP micro-orifice uniform deposit impactor (MOUDI) with 0.1–18 μm aerodynamic diameter range, and a TSI electrical aerosol analyser which counts particles larger than 0.01 μm in aerodynamic diameter. Sanders, Xu, Dalka, and Maricq (2003) investigated wear debris from brakes with LM, NAO and SM pads. The tests were conducted on a brake dynamometer in two regimes: wind tunnel and test track. The measurements were made using an ELPI, a MOUDI, and a TSI aerodynamic particle sizer (APS) with 0.5–20 μm aerodynamic diameter range. Iijima et al. (2007) investigated abrasion dusts from a brake dynamometer with NAO pads. A Tokyo Dylec APS was used to classify particles in the aerodynamic diameter range of 0.5–20 μm.

Kukutschová et al. (2011) performed a brake dynamometer study of particles emitted from brakes with LM pads. The measurements were made using a 0.01–0.445 μm range TSI scanning mobility particle sizer (SMPS) and a TSI APS. Wahlström, Söderberg, Olander, Olofsson, and Jansson, (2010a), Wahlström, Olander, and Olofsson (2010b) and Wahlström, Olander, and Olofsson (2012) conducted laboratory and field studies of particulate matter emissions from LM and NAO brake materials. The particles were counted and classified by size using a 0.02–1 μm range TSI P-Trak condensation nuclei counter, a 0.02–0.3 μm range NanoCheck sensor, a 0.25–32 μm range GRIMM optical aerosol spectrometer, and a 0.1–10 μm range TSI DustTrak aerosol monitor (DustTrak). Hagino, Oyama, and Sasaki (2015) investigated particle emissions from a brake dynamometer with NAO pads under different driving conditions. The particle mass concentrations were measured by two DustTrak II particle mass monitors. Alemani, Nosko, Metinoz, and Olofsson (2016) performed a pin-on-disc study of particles generated by LM/cast iron and NAO/cast iron pairs under steady sliding conditions. The measurements were made using a Dekati ELPI+ with 0.006–10 μm aerodynamic diameter range, a 0.0056–0.56 μm range TSI fast mobility particle sizer (FMPS), and a 0.3–10 μm range TSI optical particle sizer (OPS). Nosko, Alemani, and Olofsson (2015) investigated the influence of temperature on particle emissions from LM/cast iron pairs using a pin-on-disc machine in a sealed chamber. The particles were counted and size classified by an FMPS and an OPS.

This literature review shows that airborne particles generated by car brakes have been investigated in terms of concentration and size distribution. Nonetheless, the quantification of wear particles remains a difficult task because of the differing size and mass characteristics measured by different aerosol instruments. For example, particle emissions can be described in terms of a mobility size distribution and an aerodynamic size distribution (Charvet, Bau, Bémer, & Thomas, 2015; Maricq, Podsiadlik, & Chase, 2000), a measured particle mass concentration and a mass concentration calculated from a particle size distribution (Kousaka, Okuyama, Endo, & Tanaka, 1981; Pitz et al., 2003), an aerodynamic diameter of a particle and its geometric diameter (Kasper, 1977), or a mobility diameter of a particle and its mass (McMurry, Wang, Park, & Ehara, 2002). In most cases, the mentioned difficulty can be overcome if the so-called effective particle density is known. The effective density is an aerosol property that is intimately connected