Atmospheric Environment 97 (2014) 195–205

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

On-road and laboratory investigations on non-exhaust ultrafine particles from the interaction between the tire and road pavement under braking conditions

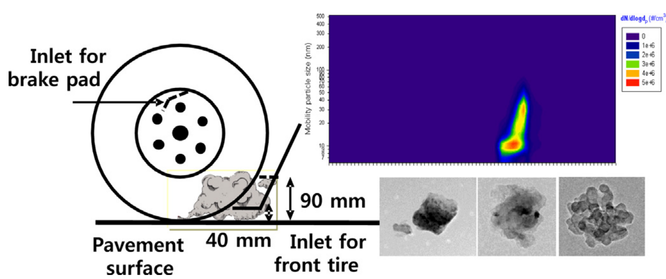
Jihyun Kwak [a], Sunyoup Lee [b], Seokhwan Lee [b,*]

[a] Accident Response Coordination Division, National Institute of Chemical Safety, 90, Gajeongbuk-ro, Yuseong-gu, Daejeon 305-343, Republic of Korea
[b] Department of Engine Research, Korea Institute of Machinery and Materials, 156, Gajeongbuk-ro, Yuseong-gu, Daejeon 305-343, Republic of Korea

HIGHLIGHTS

- We investigate the physical and chemical characterization of non-exhaust particles.
- Ultrafine particles were measured during on-road driving and in a laboratory.
- The particle number and size distributions were observed under various conditions.
- The morphological and elemental analyses can inform the particle formation.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 17 March 2014
Received in revised form
31 July 2014
Accepted 1 August 2014
Available online 6 August 2014

Keywords:
Tire particles (TPs)
Brake particles (BPs)
On-road driving
Laboratory measurement
Morphological and elemental analyses

ABSTRACT

We investigated the physical and chemical characteristics of non-exhaust ultrafine particles from on-road driving and laboratory measurements using a mobile sampling vehicle. The on-road driving and laboratory measurements during constant speed conditions revealed no enhancement of ultrafine particles. Under braking events, the total number concentrations of tire particles (TPs) sampled 90 mm above the road surface was 6 times higher with broader mode diameters when compared to 40 mm above the road surface. In contrast to braking events, under cornering conditions, the total number concentrations of TPs sampled 40 mm above the road surface were 50 times higher relative to 90 mm above the road surface. From the morphological and elemental analyses, it is likely that the ultrafine particles generated from the interaction between the tire and the road surface under braking conditions might originated from sulfur-containing materials or anti-oxidants which are contained in TPs, and/or graphite and solid lubricants which are mainly present in brake particles (BPs). However, Zn which was a distinguishing elemental marker of tire wear particles didn't show in EDS spectra. Further research would be required as to the exact emission source of ultrafine particles.

1. Introduction

Ambient ultrafine particles (<100 nm) are known to affect the Earth's climate and human health. These particles were found to be involved in scattering and absorbing solar radiation or in acting as cloud condensation nuclei (IPCC, 2007). In addition, there have been strong relationships between exceeding concentrations of the

* Corresponding author.
E-mail addresses: kkjh5950@korea.kr (J. Kwak), sunylee@kimm.re.kr (S. Lee), shlee@kimm.re.kr (S. Lee).

http://dx.doi.org/10.1016/j.atmosenv.2014.08.014
1352-2310/

ultrafine particles and adverse health effects such as increasing mortality (Ezzati et al., 2002; Ibald-Mulli et al., 2002), as well as increased respiratory and cardiovascular disease (Hoek et al., 2002; Peters et al., 2001; Pope et al., 2002). Several studies reported that nano-size particles are more toxic than their larger counterparts of same materials and complex interactions between the particles and gaseous components may act synergistically to increase their toxic effects (Biswas and Wu, 2005; Faux, 2003).

A number of studies have reported that significant quantities of ultrafine particles were emitted from exhaust gases of diesel engines or alternatives to conventional base diesel vehicles (Holmén and Ayala, 2002; Kittelson et al., 2006; Xinling and Zhen, 2009). However, as the control regulation for diesel exhaust resulted in a reduction in emissions from individual vehicles, the relative contribution from non-exhaust sources such as tire particles (TPs) emitted from the interaction between the tire and the road surface, and brake particles (BPs) is increasing (Dahl et al., 2006; Gustafsson et al., 2010; Mathissen et al., 2011; Kumar et al., 2013). Dahl et al. (2006) determined the size distributions of ultrafine particles of studded and non-studded tires depending on different types of pavements using a road simulator. They reported that the mean particle diameters emitted from the tires ranged between 15 and 50 nm with highest number concentrations in studded tires and these particles presumably originated from the tire and not the pavement. However, in the study of Gustafsson et al. (2010), they found that ultrafine particles of size 30–50 nm only occur during tests with studded tires and the major contributor of ultrafine particles is pavement wear than tire wear. In the study of Mathissen et al. (2011), on-road measurements of ultrafine particles were investigated from the tire–road interfaces and near the brake pad on different driving conditions using summer tires and revealed that the nanoparticle numbers significantly increased near the tire–road interface and brake pad during braking events.

In addition to investigating tire-related ultrafine particles, several authors have characterized brake-related ultrafine particles. Kukutschová et al. (2011) investigated wear particles released from "low-metallic" automotive brake pads using brake dynamometer tests and reported that airborne wear particles had size ranges from 10 nm to 20 μm and the numbers of ultrafine particles (<100 nm) were by three orders of magnitude larger when compared to the microparticles. In addition, the authors emphasized that since the friction process involves heat and high pressures on the friction interface, the structure and chemistry of released particles differs from the bulk friction material of the brake. Garg et al. (2000) and Sanders et al. (2003) also performed similar brake wear study using a brake dynamometer and observed large particle number concentrations.

However, no attempt has been made to simultaneously investigate the ultrafine particles produced from the tire and the brake in both on-road driving and laboratory measurements. Thus, in this study, on-road measurements were conducted to investigate the physical and chemical characteristics of ultrafine particles in different driving situations (constant speed, braking, and cornering). In addition, the effect of the sampling location from the interaction between the tire and road surface on the size distributions or number concentrations of ultrafine particles was considered. The on-road measurements were compared to those obtained from a road simulator study to identify the exact sources and to better understand the generation mechanism of ultrafine particles emitted from the tire or the brake.

2. Experimental methods

2.1. Mobile sampling vehicle

A schematic of the mobile sampling vehicle employed in this study is provided in Fig. 1. The current mobile sampling vehicle employed in this study has been well described in previous research (Kwak et al., 2013a). The vehicle has an unloaded weight of 1400 kg and is powered by a 2000 cc gasoline engine. Because studded tires are not used in South Korea, all the experiments were conducted using summer tires (Kumho KH25 225/45/R18, UTQG (Uniform Tire Quality Grade Standards) tread wear 480). Sampling inlets were installed in front of the vehicle to measure background reference concentrations (Fig. 1(1)), behind the front tire to measure particles generated from the interaction between the tire and road surface (here defined as tire particles, TPs) (Fig. 1(2)), and close to the brake pad to sample particles produce by brake wear and perhaps other materials generated from the tire/road interface during braking conditions (here defined as brake particles, BPs) (Fig. 1(3)). Despite being defined as the particles generated from the tire–road surface interaction, the TPs may be influenced by various sources such as tire, brake, road surface wear, road dust, and atmospheric depositions, etc. and sampled together with them. In particular, to investigate the effect of the sampling location on the size distributions or number concentrations of TPs, the sampling inlets were installed 40 mm (the minimum height as close as possible with the road surface without touching) and 90 mm (as far as possible with the road surface considering the space constraints) above the road surface, respectively. The brake pad used in our mobile sampling vehicle is non-asbestos organic (NAO) type and typically comprises binders, fibers, fillers, lubricants, and modifiers (Kim et al., 2007). The differences between (2) and (1) or between (3) and (1) were considered as the net particle number concentrations of TPs or BPs, respectively.

All sampling inlets were connected to sampling plena, which had an inner diameter of 48 mm, and an air flow velocity of 0.58 m/s with the Reynold's number of 1858 (laminar flow). The ultrafine particles were drawn with a flow rate of 63 L/min^3 (LPM) by a pump connected to the sampling plena and measured by different particle-monitoring instruments. Conductive tube with an inner diameter of 10 mm and length of 1 m was used for lining from the plenum to particle monitors.

2.2. Sampling site and driving condition

For on-road measurements, it is important to maintain constant vehicle speed and to exclude the emissions from nearby vehicles which can aggravate the reliability of our measurements. Thus, all the experiments were conducted on a high-speed circuit and round track at the Korea Automobile Testing & Research Institute (KATRI) proving ground in Hwaseong, South Korea. The proving ground was constructed in 2002 and is made of asphalt concrete (KSF2349, <19 mm), which is a mixture of small stones, sands, filler and bitumen. The proving ground is outside the metropolitan area and, thus is free from the anthropogenic air pollution sources.

In the high-speed circuit having a 5.5 km distance, "constant speed driving" and "braking" conditions were conducted. In the "constant speed driving", constant driving conditions with no steering movements of 50, 80, 110, and 140 km/h were tested. Under "braking" condition, the vehicle gradually starts from 0 to 150 km/h with acceleration rate of 0.54–1.54 m/s^2 and stops with deceleration rate of 2.87–4.16 m/s^2. In the round track with a diameter of 50 m, "cornering" was performed with constant velocity of 50 km/h and a lateral acceleration of 5.1 m/s^2. All on-road measurements at the high-speed circuit and the round track were repeated at least three times ($n = 3$), and performed on 15 June 2012 and 13 August 2013. The average temperature and the relative humidity were 23 °C and 65% on 15 June 2012, and 30 °C and 75% on 13 August 2013.

In the proving ground, it is difficult to exclude previously deposited particles on the road; hence, we performed the road