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Size distribution analysis of airborne wear particles released by subway brake system

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ABSTRACT

Contributions of exhaust and non-exhaust sources to traffic-related particulate matter (PM) pollution in the atmosphere are almost identical and the most important non-exhaust source is known to be brake wear particles. In order to understand the properties and harmful effects of wear particles on people, accurate information on size distribution of brake wear particles is needed. Our previous study investigated the measured changes in size distribution of nanoparticles of 500 nm or smaller to understand the origin of nanoparticles due to temperature increases on the friction surface. The present study was intended to investigate the characteristics of size distribution (5.6 nm–32 μm) of PM released under different braking conditions by using different instruments. The measurement results under 9 braking conditions using 3 different instruments showed that the size distribution characteristics of particles can be divided into two main types according to braking energy. The first type is of PM up to 10 μm in size and with a peak number concentration at 0.2–0.75 μm regardless of braking energy, while the second type is of PM around 10 nm in size generated only when braking energy increased and particles that increased up to 100 nm. In addition, we found that the size distributions measured by the optical particle counter (OPC) and the aerodynamic particle sizer (APS) were consistent by assuming a mean diameter ratio of two instruments.

1. Introduction

The disk - brake pad brake system applied in vehicles and trains converts kinetic energy of those vehicles into thermal energy and inevitably releases wear particles from friction during the braking process. The characteristics of such generation of wear particles differ according to a variety of factors such as brake type, brake and pad material and elements, initial brake velocity, braking-contact force, vehicle operating conditions and testing method [1–6]. Brake disc and pad materials are the same as those used with automotive vehicles and subway brakes. Although some released wear particles may be deposited on the surface of the brakes and the road, 35–50% of them remain suspended in the air as airborne particles [1,3]. Although the technology to reduce vehicle emission pollutants from combustion engines continues to improve as a way of coping with constantly-tightening regulations on vehicle exhaust gas and particles, the development, or even study, of technology to reduce non-exhaust sources of particles such as brake wear, tire wear and re-suspension of existing road dust is relatively limited, while the contribution of non-exhaust sources to pollution of the urban atmosphere is expected to gradually increase [7]. In a review paper on brake wear particles, Grigoratos and Martini [5] summarized that the contributions of exhaust and non-exhaust sources to traffic-related PM_{10} were almost identical and that the most important non-exhaust source was brake wear.

There have been many studies on size distribution and elements of brake wear particles [4,8–11]. There are also reports on the evaluation of the harm brake wear particles pose to the human body [12–15], their contribution to atmospheric pollution [16–19], and calculation of emission factors [1,20–22]. Findings and limitations from these studies, as they relate to distribution of number concentration of airborne wear particles released by brake wear, are summarized below.

Sanders et al. [3] observed a stiff increase in number

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concentration of 0.3 μm or smaller sized particles under severe braking conditions by using cascade impactors. Mosleh et al. [8] found the common peak in the range of 0.3–0.4 μm and the second peak in the range of 1–10 μm according to braking conditions in a pin-on-disc test. Iijima et al. [20] reported their observation of unimodal size distribution showing a constant peak at 0.8 μm under different braking conditions using an aerodynamic particle sizer (APS, TSI Inc.). WahlstrÖm et al. [11] observed the bimodal peak of 0.28 μm and 0.35 μm by using the aerosol spectrometer (Grimm 1.109). Kukutschova et al. [9] measured the brake wear particles using the scanning mobility particles sizer (SMPS; TSI Inc.) and ASP but they did not describe the 0.45–0.5 μm particles that were not included in the measurement range of either SMPS or APS. Mathissen et al. [23] observed the generation of nucleation mode particles at around 10–60 nm during conditions of full braking using an engine exhaust particle sizer (EEPS; TSI Inc.). Abbasi et al. [24] also observed peak in the ultrafine region of around 100 nm using the aerosol spectrometer (Grimm 1.109) and SMPS.

A review of these studies on size distribution of wear particles released by braking shows that there were limitations in size analysis method according to the measurement limitations (size measurement limitations) of the measuring equipment or the principle of measurement. There are few comprehensive studies that analyze size distribution of all sizes of wear particles that can range from several nanometers to tens of micrometers. Our previous study investigated the measured change in size distribution of nanosized particles of 500 nm or smaller every second under various braking conditions to investigate the evaporation-condensation-coagulation phenomenon of brake pad elements due to temperature increase of the friction surface [25]. This study was intended to analyze the results of size measurements from particle measuring devices applying different measuring principles (light-scattering method and time-of-flight method) that are different from the test in our preceding study, as well as to investigate the characteristics of size distribution in the range of 5.6 nm–32 μm of particulate matter released under different braking conditions. It will also present a method of interpreting the measurement results of the aerosol spectrometer and APS, which have similar measurement ranges.

2. Method

2.1. Braking test

To measure brake wear dust, a brake disk and a non-asbestos organic (NAO) brake pad used in subway trains were mounted, and the particles released under various braking conditions analyzed. NAO brake pads contain nonferrous metals, inorganic and organic fibers, abrasives, lubricants and property modifiers such as glass, rubber, synthetic fiber and carbon but the exact composition rate of the pads is unknown. Braking tests were conducted using the real-scale brake dynamometer which met UIC code 541-3, international standards [26]. The brake dynamometer has 400 km/h of the maximum applicable speed and 60kN of the maximum brake force. Details of the test were presented in our previous study [25]. The test system was configured to measure the airborne wear particles released under various braking conditions using three particle sizing instruments through the flow splitter (TSI, 3708): the fast mobility particle sizer (FMPS; TSI 3091), aerodynamic particle sizer (APS; TSI 3321), and the optical particle counter (OPC; Grimm 1.109) simultaneously (Fig. 1). Braking conditions were set to 9 cases at three braking-contact forces (12 kN, 20 kN, 30 kN) at each of three initial braking velocities of 25 km/h, 50 km/h, and 100 km/h.

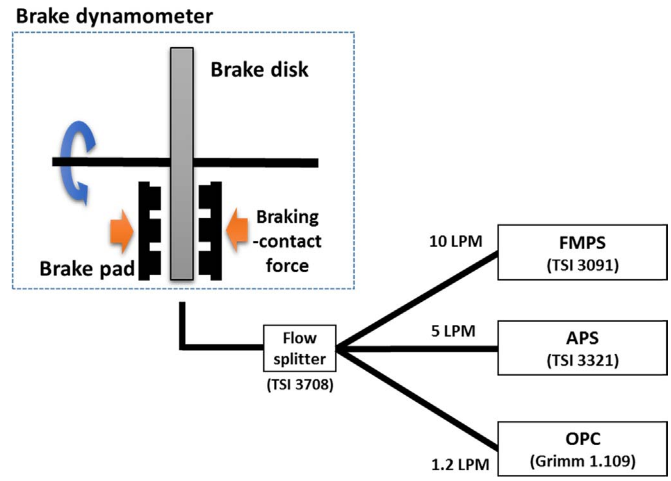

Fig. 1. Experimental setup of full-scale brake dynamometer for airborne wear particle sizing.

2.2. Measurement of size distribution

Table 1 shows the specifications of particle sizing instruments used to measure the airborne particles (aerosols) released during braking. FMPS controls the charging state of each particle in the size range of 5.6–560 nm to measure the size according to the difference of electrical mobility and provides size distribution data every second through 32 channels. The APS measures the time-of-flight of particles passing through an accelerated nozzle to calculate aerodynamic diameter of unit-density spherical particles in the 0.5–20 μm range, and also provides size distribution data through 32 channels every second. In the case of APS, the data in the first channel (bin 1), which measures particles up to 0.523 μm, were excluded from analysis [27]. OPC measures the light scattering intensity of single particles to calculate the size and provides size distribution through 31 channels every 6 s. Unlike FMPS, which measures nanoparticles of 560 nm or smaller, APS and OPC have similar size measurement ranges. However, care needs to be exercised when interpreting physical size of actual particles released during braking and the results of size measurement from each instrument since FMPS measures size based on electrical mobility of particles, APS measures time-of-flight to calculate aerodynamic diameters of particles of 1 g/cm^3 in density, while OPC measures size based on light-scattering intensity of particles.

2.3. Data analysis

The size distributions of particles were measured using three instruments during the braking time (t_B; time from beginning of braking to actual stopping), simultaneously. FMPS and APS provided size distribution data every second while OPC provided them every 6 seconds. Since the braking time under each braking condition differs according to initial velocity (V_i) and braking-contact force (F_B) as shown in Table 2, the mean concentration of each size throughout the entire braking time under each braking condition was analyzed. The concentration of background particles, which existed when braking is not applied, was measured before and after the testing and excluded from analysis. Braking energy (E_B) is expressed by multiplication of the specific braking-contact force at the initial braking velocity to the distance traveled until the braking is complete. Since the velocity decreases in a linear manner after braking is applied, braking distance can be expressed as 1/2 the multiplication of the initial velocity by the braking time as Eq. (1):