Aerosol and Air Quality Research, 10: 22–29, 2010

ISSN: 1680-8584 print / 2071-1409 online
doi: 10.4209/aaqr.2009.05.0037

Measurement of Particle Mass Concentrations and Size Distributions in an Underground Station

Yu-Hsiang Cheng*, Yi-Lun Lin

Department of Safety, Health and Environmental Engineering, Ming Chi University of Technology, 84 Gungjuan Rd, Taishan, Taipei 24301, Taiwan

ABSTRACT

The Taipei main station is a major transfer station in the Taipei Rapid Transit System and is located at the center of Taipei metropolitan areas. This study investigates particle mass concentrations and size distributions at the concourse in this underground station using an optical particle counter. On-site measurements were taken during January–February 2008. Experimental results show that PM_{10} and $PM_{2.5}$ levels in the Taipei main station were 9.83–104.26 μg/m^3 and 3.84–59.74 μg/m^3, respectively. The lognormal mass size distribution in the Taipei main station had two modes; one near 0.27 μm and the other at about 12.5 μm. Additionally, the mean mass concentrations were governed by particles with coarse PM. Measurement results also suggest that average PM_{10} and $PM_{2.5}$ levels in the indoor station were about 0.70 and 0.53 times those outdoors, respectively. The PM levels in the indoor station and outdoors were positively correlated, indicating that PM levels at the concourse in the Taipei main station are significantly influenced by outdoor ambient PM levels. Moreover, the low $PM_{2.5}$-to-PM_{10} ratio at the concourse in the Taipei main station was likely the result of coarse PM being re-suspended in the station concourse due to passenger movement.

Keywords: PM_{10}; $PM_{2.5}$; Size distribution; Underground station; Optical particle counter.

INTRODUCTION

Suspended particulate matter (PM) is recognized to have a strong impact on the environment and to be of concern in health related effects. The particulate matter PM_{10} fraction and especially $PM_{2.5}$ fraction can reach conductive airways and adversely affect the respiratory system (Duhme *et al.*, 1998). Recent epidemiological studies have demonstrated that airborne PM in urban areas has a clear correlation with the respiratory and cardiovascular diseases responses (Pope *et al.*, 2004). The mechanisms behind these effects include oxidative stress and inflammation. Pope *et al.* (2002) determined that each 10 μg/m^3 increase in fine particulate concentration was associated with an approximate 4%, 6% and 8% increase in risk of all-cause, cardiopulmonary and lung cancer mortality, respectively.

In urban areas, residents usually spend a considerable amount of time commuting. Subway systems are major transportation modes typically serving billions of passengers annually in metropolitan areas worldwide. High concentrations of PM have been measured in many subway systems, such as those in London (Pfeifer *et al.*, 1999; Sitzmann *et al.*, 1999; Adams *et al.*, 2001; Seaton *et al.*, 2005), Stockholm (Johansson and Johansson, 2003), Prague (Braniš, 2006), Rome (Ripanucci *et al.*, 2006), Berlin (Fromme *et al.*, 1998), Seoul (Kim *et al.*, 2008; Park and Ha, 2008) and Beijing (Li *et al.*, 2007). Moreover, Karlsson *et al.* (2005) compared the ability of particles from a subway station and a nearby very busy urban street, respectively, to damage DNA and to induce oxidative stress. Experimental results demonstrated that the subway particles were approximately 8 times more genotoxic and 4 times more likely to cause oxidative stress in the lung cells. Even though some of the authors have made an effort to measure PM levels on the platforms and in trains in the subway systems. The PM levels at the station concourse in an underground were never investigated in former studies. It is interesting to know that the PM levels at the station concourse in an underground station where commuters stay. Therefore, routine monitoring of PM concentrations to evaluate environmental exposure at the station concourse in the underground subway stations is important.

The Taipei main station, a major transfer station in the Taipei Rapid Transit System (TRTS), is located at the center of Taipei metropolitan areas. This station serves passengers transferring to different subway lines, the Taiwan railway system (TRS) and Taiwan's high-speed railway (THSR). However, data for indoor air quality at

* Corresponding author. Tel.: +886-2-29089899;
Fax: +886-2-29084513
E-mail address: yhcheng@mail.mcut.edu.tw

the station concourse in the Taipei main station are limited, especially for particle mass concentrations and size distributions. This study investigates particle mass concentrations and size distributions at the concourse in this underground station using an optical particle counter. The result of a size distribution analysis might be able to provide the characteristics of the particulate matters in the underground station. Outdoor hourly PM_{10} and $PM_{2.5}$ levels measured by an ambient air-quality monitoring station near the Taipei main station are used to evaluate the relationship between underground PM levels and outdoor ambient PM levels.

MATERIAL AND METHODS

Sampling Site and Data Collection

The Taipei main station is one of two major transfer stations in the TRTS. In this study, the monitoring location selected was the concourse in the Taipei main station (on the third basement floor) where commuters purchase tickets, enter or exit the TRTS, TRS and THSR. Thus, the Taipei main station is the busiest of the all stations in the TRTS. The particle mass concentrations and size distributions were measured using a portable dust monitor. On-site measurements were taken 8 times during January–February 2008. During monitoring periods, the dust monitor was operated individually for about 7 h (11:00–18:00) at five times on-site monitoring and operated with a reference sampler for about 17 h (7:00–23:00) at three times on-site monitoring.

Hourly outdoor PM_{10} and $PM_{2.5}$ levels measured by ambient air-quality monitoring stations at Zhondshan station near the Taipei main station are considered the PM levels in outside the station. These hourly PM_{10} and $PM_{2.5}$ concentrations were measured by automatic Met One BAM 1020 beta gauge monitors (Met One, Inc., Grants Pass, OR, USA) in Taiwan's air-quality monitoring network. The data procedure of the air-quality monitoring network was guaranteed by Taiwan's EPA and these monitoring data can be gotten from Taiwan's EPA.

Monitoring Equipment

In this study, the Grimm Series 1.108 Aerosol Spectrometer (Grimm Technologies, Inc., Douglasville, GA, USA), a portable optical particle counter, was utilized to measure particle mass concentrations and size distributions since this kind of monitor is lightweight, easy to operate, and effective for time resolution.

The Grimm Aerosol Spectrometer measures the number of particles per unit volume of air using light-scattering technology. The number concentration of aerosol particles detected by the spectrometer is converted into a mass concentration via mathematical extrapolation with a correction factor. The relationship between the mass concentration and number concentration can be expressed as

$$m(d_{pi}) = C_F \frac{\pi}{6} d_{pi}^3 n(d_{pi}) \quad (1)$$

where i is channel number of the optical particle counter; d_{pi} is the arithmetic mean diameter of the upper and lower boundaries for channel i; $m(d_{pi})$ is the mass concentration in channel i; $n(d_{pi})$ is the number concentration in channel i; and C_F is a correction factor. In this study, measurement raw data are reported based on the default correction factor of 1.0.

This instrument provides four operational modes: environmental, occupational health, mass distribution and count distribution. The instrument measures particle concentrations in an optical size of 0.23–20 μm in 15 channels with differently sizes with a concentration range of 1–2,000,000 particles/L (for count distribution mode) or a mass concentration range of 1–100000 $\mu g/m^3$ (for mass distribution, environmental and occupational health modes). Spectrometer sensitivity is 1 particle/L or 1 $\mu g/m^3$, and instrument reproducibility is ± 2%. Ambient air is drawn into the unit via an internal volume-controlled pump at a rate of 1.2 L/min. At the start of each measurement, the instrument initiates a system self-test and zero calibration check. A stainless steel tube provided by the manufacturer was utilized as the spectrometer inlet.

In this study, the spectrometer was operated in mass distribution mode to produce mass concentrations versus time. The measured real-time mass concentration data are transferred at 1-minute intervals to a data storage card. Measurement data were then downloaded from the storage card via the Grimm 1177 program on mass distribution mode and environmental mode, respectively. The particle mass concentrations in 15 different sizes can be produced at mass distribution mode. Additionally, PM_{10}, $PM_{2.5}$ and $PM_{1.0}$ levels can be generated directly when environmental mode was selected.

Moreover, the PM_{10} and $PM_{2.5}$ levels were also calculated from particle mass concentrations (obtained from mass distribution mode) with PM_{10} and $PM_{2.5}$ fractions to compare with those produced directly on environmental mode. The PM_{10} and $PM_{2.5}$ levels were computed as follows:

$$PM = \sum_{i=1}^{15} m(d_{pi}) f(d_{pi}) \quad (2)$$

where PM is PM_{10} or $PM_{2.5}$ and $f(d_{pi})$ is the fraction of PM_{10} or $PM_{2.5}$ at d_{pi} (Hinds, 1999). The fraction of PM_{10} and $PM_{2.5}$ can be estimated by

$$f_{PM10}(d_{pi}) = 1.0 \quad \text{for } d_{pi} < 1.5\ \mu m \quad (3)$$

$$f_{PM10}(d_{pi}) = 0.9585\text{-}0.00408 d_{pi}^2 \quad \text{for } 1.5 < d_{pi} < 15\ \mu m \quad (4)$$

$$f_{PM10}(d_{pi}) = 0.0 \quad \text{for } d_{pi} > 15\ \mu m \quad (5)$$

$$f_{PM2.5}(d_{pi}) = \left[1 + exp(3.233 d_{pi} - 9.495)\right]^{-3.368} \quad (6)$$

where d_{pi} is the diameter in μm.

Data Quality Assurance

However, the responses of light-scattering dust monitors are influenced by aerosol parameters such as the refractive index, and particle shape, density and size. Therefore, to acquire accurate quantitative measurements of aerosol concentrations, the Grimm Aerosol Spectrometer was compared with an equivalent method with the target dust under the same environmental conditions as it was utilized to evaluate the PM levels. During three of eight times field monitoring sessions, a Met One E-BAM sampler (Met One, Inc., Grants Pass, OR, USA) was placed beside a Grimm Aerosol Spectrometer and used as a reference sampler to assess the Grimm Aerosol Spectrometer performance at the concourse in the Taipei main station. The Met One E-BAM sampler is an automatic air monitor based on beta attenuation and it was a lightweight, potable type beta gauge which is easily mounted on a tripod in an indoor environment to measure hourly PM levels. Furthermore, beta attenuation approach has been certified by Taiwan's Environmental Protection Agency (EPA) as an effective method (Taiwan EPA NIEA A206.10C).

Sampling flow rate of the Met One E-BAM sampler was 16.7 L/min with a US EPA-designed PM_{10} inlet head (BX-802, Met One, Inc., Grants Pass, OR, USA) to measure hourly average PM_{10} levels. A $PM_{2.5}$ cut-size WINS impactor (BX-804, Met One, Inc., Grants Pass, OR, USA) can be installed at the downstream of the PM_{10} inlet when the Met One E-BAM sampler was used to measure hourly average $PM_{2.5}$ levels. The Met One E-BAM sampler was operated with an inlet heater to eliminate water condensing on the filter. In each field monitoring, the E-BAM beta gauge monitor was checked with the zero and span calibration plates to audit the measuring system. The Grimm Aerosol Spectrometer and Met One E-BAM were operated continuously for approximately 17 h during each on-site sampling period (7:00–23:00) to measured hourly average PM_{10} or $PM_{2.5}$ levels. A calibration factor for the Grimm Aerosol Spectrometer was determined by comparing the relationship between PM mass concentrations measured by the Met One E-BAM sampler and that measured using the Grimm Aerosol Spectrometer. The raw data obtained by the Grimm Aerosol Spectrometer were calibrated with a correction factor to estimate "actual" PM levels in the Taipei main station.

The paired samples t-test was performed to analyze the differences in PM levels between the indoor station and outdoors. The significance level was 0.05 for all statistical tests. The Pearson product moment correlation coefficient ($R_{Pearson}$) was applied to assess any correlation between metro station PM levels and outdoor ambient PM levels.

RESULTS AND DISCUSSION

Calibration Factor for Grimm Aerosol Spectrometer

Fig. 1(a) presents the relationship between 1-h average PM concentrations generated directly from the Grimm Aerosol Spectrometer in environmental mode and those measured by the Met One E-BAM sampler at the station concourse in the Taipei main station. Statistical results indicate that the calibration factor for PM levels those generated directly from the Grimm Aerosol Spectrometer in environmental mode is 0.86 (R^2 = 0.99). Experimental results suggest that PM levels measured by theGrimm Aerosol Spectrometer in environmental mode overestimated PM concentrations in the underground station by about 1.2 times. Fig. 1(b) presents the relationship between 1-h average PM concentrations calculated from mass distribution data of the Grimm Aerosol Spectrometer with PM fractions (Eqs. (2)–(6)) and those measured by the Met One E-BAM sampler at the station concourse in the Taipei main station. Statistical results indicate that the calibration factor for mass concentration those produced from the Grimm Aerosol Spectrometer in mass distribution mode is 0.59 (R^2 = 0.99). Cheng (2008) reported that the Grimm Aerosol Spectrometer underestimated PM levels by about 0.75 times the actual concentration in an iron foundry. Based on measurement results in this study and those obtained by Cheng (2008) indicated that optical responses of different particles may vary significant, depending on their refractive indexes, densities, and shapes; that is, a suitable calibration factor is required for the Grimm Aerosol Spectrometer in different environments.

The PM levels calculated using Eqs. (2)–(6) are significantly greater about 1.46 times than those generated directly by the spectrometer in environmental mode. Experimental results suggest that PM levels measured by the spectrometer in environmental mode and those calculated from the particle mass size distribution with the PM_{10} and $PM_{2.5}$ fractions are inconsistent. It is interesting to note that PM levels calculated using Eq. (2) with the PM_{10} and $PM_{2.5}$ fractions provided by the manufacturer were also inconsistent with those generated directly by the spectrometer in environmental mode. Comparison results indicated that there exist some mistakes in the Grimm 1177 program used to calculate PM levels. However, experimental results indicate that the spectrometer required calibration prior to measuring PM levels. The raw data obtained by the Grimm Aerosol Spectrometer in environmental mode and mass distribution mode were calibrated with correction factors 0.86 and 0.59, respectively, to estimate "actual" PM levels and mass size distributions at the station concourse in the Taipei main station.

PM Levels and Mass Size Distributions in the Taipei Main Station

Table 1 presents the hourly average PM_{10}, $PM_{2.5}$ and particle mass size distributions at the station concourse in the Taipei main station. Experimental results show that PM_{10} and $PM_{2.5}$ levels at the station concourse in the Taipei main station were 9.83–104.26 μg/m^3 (mean = 39.98 μg/m^3) and 3.84–59.74μg/m^3 (mean = 16.38 μg/m^3), respectively. The highest and second-highest mass concentrations of particle fractions at the station concourse in the Taipei main station were in the 10–15 μm (mean = 16.63 μg/m^3; 24.17%) and 15–20 μm (mean = 10.55 μg/m^3; 15.59%) fractions, respectively.

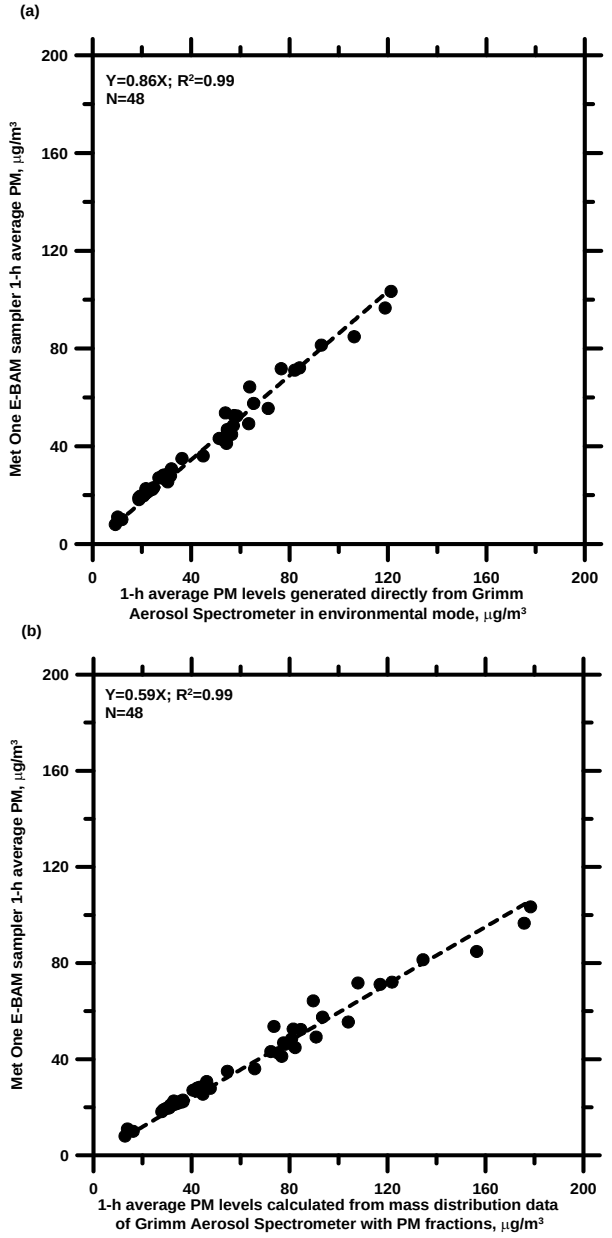

Fig. 1. Scatter plot of the 1-h average PM measurements by the Grimm Aerosol Spectrometer vs. the Met One E-BAM sampler: (a) PM levels generated directly from Grimm Aerosol Spectrometer in environmental mode; (b) PM levels calculated from mass distribution data of Grimm Aerosol Spectrometer with PM fractions.

Fig. 2 shows the average particle mass size distribution measured at the station concourse in the Taipei main station during monitoring periods. The horizontal axis represents particle size on a logarithmic scale, whereas the vertical axis represents normalized particle mass concentration. This size distribution in the size range of 0.23–20 μm was obtained by averaging data for all monitoring periods. The upper and lower limits of the concentration error bar were defined as a single standard deviation of particle mass concentrations. Measurement results indicate that the lognormal mass size distribution at the station concourse in the Taipei main station had two modes (accumulation mode and coarse mode)—the first and second mode diameters were about 0.27 and 12.5 μm, respectively. However, the mass size distribution at the station concourse in the Taipei main station was different from that in the outdoor. The fraction of high fine particles was found in the mass size distribution for the outdoor particulate matter (Horvath *et al.*, 1996; Sillanpää *et al.*, 2005). These measurement results can be considered as that coarse PM was re-suspended on the station concourse due to passenger movement, and the fine PM could be transferred from outside traffic vehicles.

The PM levels at the station concourse in the Taipei main station are lower than those in underground stations in London (Pfeifer *et al.*, 1999; Adams *et al.*, 2001), Stockholm (Johansson and Johansson; 2003), Budapest (Salma *et al.*, 2007), Rome (Ripanucci *et al.*, 2006), Berlin (Fromme *et al.*, 1998), Seoul (Kim *et al.*, 2008; Park and Ha, 2008) and Beijing (Li *et al.*, 2007). The range and mean PM levels for these different subway systems had been described in Cheng *et al.* (2008). The PM levels at the station concourse in the Taipei main station were lower than those obtained by former studies approximately 0.1–0.4 times. However, measurement results obtained by a few studies (Chan *et al.*, 2002a; Chan *et al.*, 2002b; Aarnio *et al.*, 2005; Gómez-Perales *et al.*, 2007) are similar to those in this study. Aarnio *et al.* (2005) reported that $PM_{2.5}$ levels at station and inside trains in the Helsinki subway system were about 60 μg/m^3 and 21 μg/m^3, respectively. Chan *et al.* (2002a) obtained that PM_{10} and $PM_{2.5}$ levels inside trains in the Hong Kong mass transit railway were 44 μg/m^3 and 33 μg/m^3, respectively. Additionally, Chan *et al.* (2002b) obtained similar results, indicating that PM_{10} and $PM_{2.5}$ levels inside trains in the Guangzhou subway were 67 μg/m^3 and 44 μg/m^3, respectively. Gómez-Perales *et al.* (2007) noted that $PM_{2.5}$ levels inside trains in the Mexico City subway were about 8–68 μg/m^3.

Aarnio *et al.* (2005) proposed that the low PM levels in the Helsinki subway system were because the system is relatively new and cars have new electric braking systems that do not generate significant amounts of PM. Salma *et al.* (2007) pointed out that differences in PM levels among different subway systems may be due to different system techniques (such as car power, engineering system, emergency braking system and braking systems), station ventilation system and operational conditions. Furthermore, Kim *et al.* (2008) noted that differences in PM levels among different subway systems may be due to different monitoring conditions such as measurement time and location, seasons, equipment and outdoor climate.

Cheng *et al.* (2008) noted that the trains in the TRTS have electrical regenerative braking systems. Moreover, the TRTS has only been in operation since 1996; that is, it is new compared with systems in other countries. Thus, PM levels on platforms in the TRTS were lower than those in relatively older subway systems. However, average PM levels at the station concourse were lower than those reported by Cheng *et al.* (2008) on platforms in the Taipei main station, indicating that some PM can be generated on

Table 1. Hourly average PM_{10}, $PM_{2.5}$ and particle mass concentrations in 15 fractions.

Particle diameter, μm	Particle mass concentration, μg/m^3			
	Average [a] (S.D.[b])	Min–Max[c]	Median	Q_1–Q_3[d]
0.23–0.3	3.13 (2.56)	0.59–10.79	2.02	1.38–4.43
0.3–0.4	3.07 (2.59)	0.61–11.21	1.93	1.38–4.12
0.4–0.5	2.10 (2.10)	0.35–9.19	1.17	0.84–2.37
0.5–0.65	1.59 (1.60)	0.29–7.46	0.92	0.71–1.46
0.65–0.8	0.79 (0.73)	0.18–3.66	0.52	0.41–0.72
0.8–1.0	0.69 (0.48)	0.20–2.68	0.52	0.44–0.67
1.0–1.6	0.87 (0.46)	0.31–2.79	0.74	0.61–0.95
1.6–2.0	1.19 (0.60)	0.49–3.65	1.02	0.86–1.31
2.0–3.0	3.74 (1.86)	1.27–11.45	3.37	2.63–4.27
3.0–4.0	3.65 (1.75)	1.06–10.65	3.39	2.39–4.21
4.0–5.0	4.37 (2.20)	1.21–11.68	3.89	2.67–5.52
5.0–7.5	8.18 (4.60)	2.02–22.46	7.32	4.45–11.09
7.5–10.0	7.42 (4.62)	1.69–19.00	6.77	3.24–11.49
10.0–15.0	16.36 (10.22)	3.33–37.39	13.66	7.59–25.24
15.0–20.0	10.55 (5.84)	2.27–23.31	7.71	5.85–16.27
PM_{10}	39.98 (18.73)	9.83–104.26	39.31	21.15–50.48
$PM_{2.5}$	16.38 (10.73)	3.84–59.74	11.16	8.85–19.41

a. Observation number N = 76
b. S.D.: standard deviation.
c. Min–Max: minimal value–maximal value.
d. Q_1–Q_3: first quartile value–third quartile value.

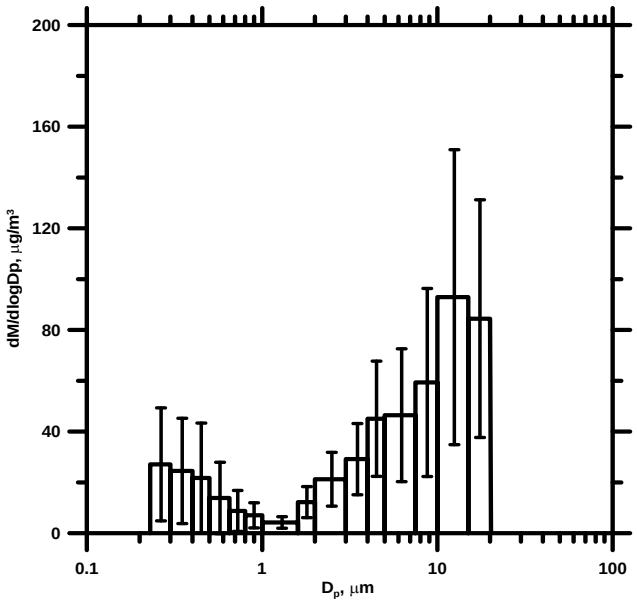

Fig. 2. Average particle mass size distribution measured in the Taipei main station during monitoring periods.

platforms. Kim *et al.* (2008) obtained similar results, suggesting that average PM levels in station offices and ticket offices were lower than those measured on platforms in Seoul subway stations.

Relationship between Indoor Station PM Levels and Outdoor Ambient PM Levels

Figs. 3(a) and 3(b) show average PM_{10} and $PM_{2.5}$ levels at the station concourse in the Taipei main station and outside the station, respectively. The hourly PM_{10} and $PM_{2.5}$ levels in the outdoor environment were 16–150 μg/m^3 (mean = 56 μg/m^3) and 2–104 μg/m^3 (mean = 34 μg/m^3), respectively. Average PM_{10} and $PM_{2.5}$ levels in the indoor station were about 0.70 and 0.53 times those outdoors, respectively. Average PM_{10} and $PM_{2.5}$ levels in the indoor station and outdoors were significantly different (all $p < 0.001$). However, the PM levels in the station and outdoors were strongly correlated ($R_{Pearson} = 0.87$ for PM_{10}; $R_{Pearson} = 0.88$ for $PM_{2.5}$), indicating that PM levels at the station concourse in the Taipei main station were markedly influenced by outdoor ambient PM levels. Braniš (2006) suggested that outdoor aerosol concentrations significantly influence air quality in underground transport systems as outdoor air enters stations via ventilation systems, station escalator tunnels and corridors. Cheng *et al.* (2008) suggested that PM can originate outside in ambient air and enter the stations via the subway tunnels.

Figs. 4(a) and 4(b) show the relationships between average $PM_{2.5}$ and PM_{10} in the indoor station and outdoors, respectively. The $PM_{2.5}$-to-PM_{10} ratios for the indoor station and outdoors were 0.43 ($R^2 = 0.91$) and 0.62 ($R^2 = 0.94$), respectively. The $PM_{2.5}$-to-PM_{10} ratio in the indoor station was significantly lower than those outdoors ($p < 0.001$). Measurement results for outdoor $PM_{2.5}$-to-PM_{10} ratio were similar to those in typical outdoor environments (Osrt and Chestunt, 1998; Harrison *et al.*, 2004; Yin and Harrison, 2008), indicating that emissions from traffic sources are dominant in $PM_{2.5}$ fraction at urban areas. The $PM_{2.5}$-to-PM_{10} ratios for different subway systems are summarized in Table 2. The $PM_{2.5}$-to-PM_{10} ratios are significantly different among these subway systems. Based

on different power systems, braking systems, ventilation systems and operational conditions among these subway systems, it should be reasonable that $PM_{2.5}$-to-PM_{10} ratios in the subway system will not be consistent for all subway systems. Chan *et al.* (2002a) noted that the ventilation system of the subway system can filter out some coarse particulates, resulting in higher $PM_{2.5}$-to-PM_{10} ratios. However, there exist significantly different measurement results of $PM_{2.5}$-to-PM_{10} ratios at line 1, 2 and 4 in Seoul subway system between Kim *et al.* (2008) and Park and Ha (2008) due to that the PM_{10} levels on station platform and inside trains measured by Kim *et al.* (2008) were significantly higher than those obtained by Park and Ha (2008) about 2–3 times. In this study, the $PM_{2.5}$-to-PM_{10} ratio at the station concourse in the Taipei main station was lower than that on station platform. Moreover, the low $PM_{2.5}$-to-PM_{10} ratio at the station concourse in the Taipei main station was likely the results of re-suspended of coarse PM in the concourse of the Taipei main station due to passenger movement. Coarse PM can also be generated by mechanical disintegration processes inside subway systems. However, coarse PM generated on platforms and inside trains within the TRTS was not significant because PM_{10} levels on platforms and inside trains were lower than those in subway systems in other countries (Cheng *et al.*, 2008).

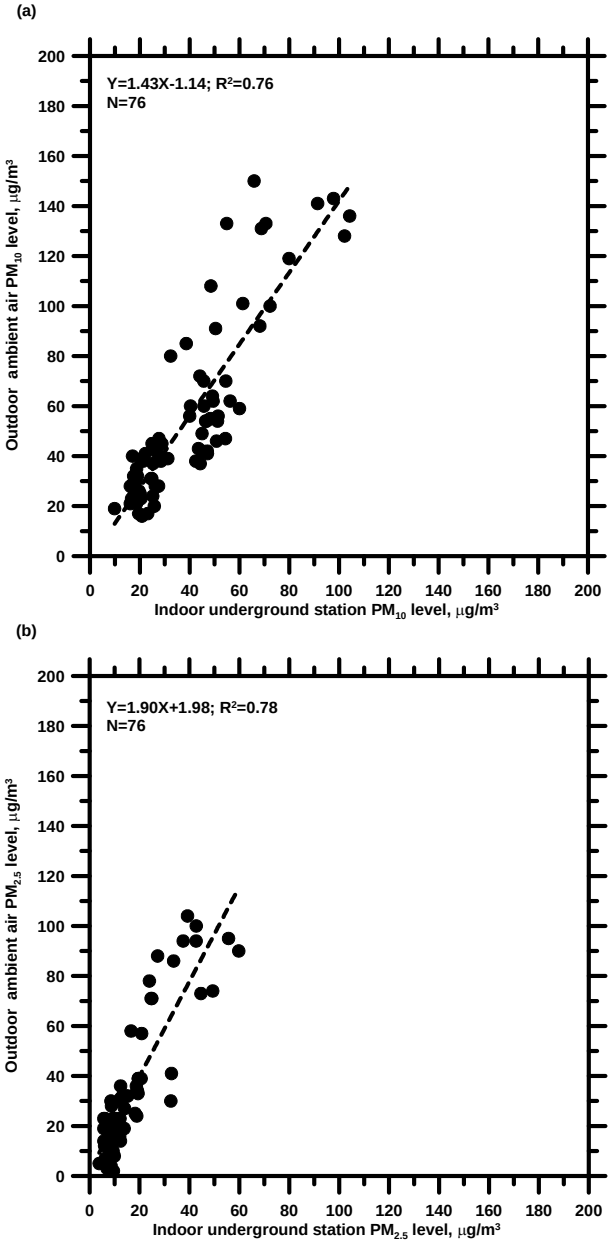

Fig. 3. Scatter plot of indoor underground station vs. outdoor ambient air: (a) 1-h average PM_{10} measurements; (b) 1-h average $PM_{2.5}$ measurements.

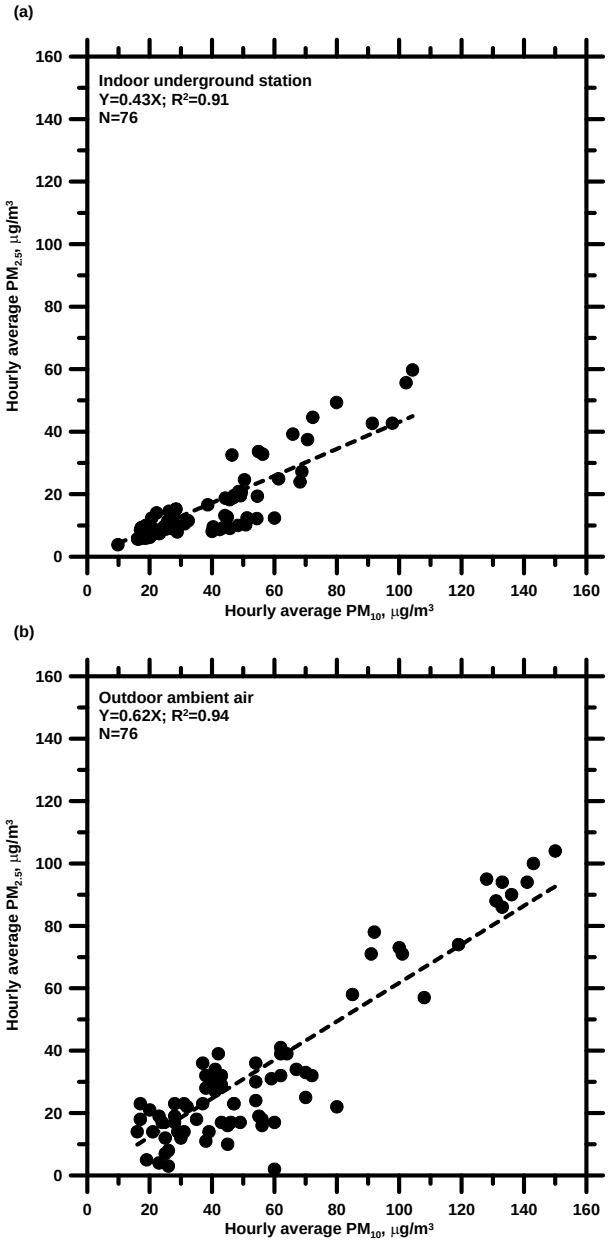

Fig. 4. Relationship between 1-h average PM_{10} and $PM_{2.5}$: (a) indoor underground station; (b) outdoor ambient air.

Based on the measurements presented here for PM levels at the station concourse in the Taipei main station, it is clear that outdoor traffic exhaust or other traffic related

Table 2. $PM_{2.5}$-to-PM_{10} ratios for different subway systems.

City	$PM_{2.5}$-to-PM_{10}	Measurement environment	Reference
Bejing	0.35	Inside trains	Li *et al.* (2007)
Guangzhou	0.79	Inside trains	Chan *et al.* (2002b)
Hong Kong	0.75	Inside trains	Chan *et al.* (2002a)
Seoul	0.36	On station platform	Kim *et al.* (2008)
	0.40	Inside trains	
	0.70	At ticket office	
Seoul	0.81	On station platform	Park and Ha (2008)
	0.80	Inside trains	
Stockholm	0.55	On station platform	Johansson and Johansson (2003)
Taipei	0.68	On station platforms	Cheng *et al.* (2008)
	0.78	Inside trains	
	0.43	At station concourse	Current study

sources can be an important source. A direct relationship between the air quality within underground railway systems and outdoor pollution levels was also identified in Helsinki and Prague (Braniš, 2006; Aarnio *et al.*, 2005). No previous data have been reported for particle mass size distributions in the underground station. According to this study, the fraction of high coarse particles was found in the mass size distribution at the station concourse in the Taipei main station. However, high PM levels in London (Pfeifer *et al.*, 1999; Adams *et al.*, 2001) and Stockholm (Johansson and Johansson, 2003) can be due to PM accumulated in ventilation systems or generated by equipment for years in old subway systems. Moreover, portable dust monitors had to be calibrated before field sampling. This study shows that PM levels measured by the Grimm Aerosol Spectrometer in environmental mode overestimated PM concentrations about 1.2 times at the station concourse in the underground station. Moreover, the mass concentrations measured by the Grimm Aerosol Spectrometer in mass distribution mode overestimated by about 1.7 times the actual mass concentrations at the station concourse in the underground station.

CONCLUSIONS

Experimental results suggest that PM levels measured by the Grimm Aerosol Spectrometer in environmental mode overestimated PM concentrations by about 1.2 times at the station concourse in the underground station. The PM_{10} and $PM_{2.5}$ levels at the station concourse in the Taipei main station were 9.83–104.26 μg/m^3 and 3.84–59.74μg/m^3, respectively. Moreover, the lognormal mass size distribution at the station concourse in the Taipei main station had two modes; one near 0.27 μm and the other at about 12.5μm. The mean mass concentrations in the 15 fractions were governed by particles with coarse PM. These measurement results can be considered as that coarse PM was re-suspended on the station concourse due to passenger movement, and the fine PM could be transferred from outside traffic vehicles. Moreover, PM levels at the station concourse in the Taipei main station were lower than those in subway systems in other countries about 0.1–0.4 times. Additionally, the average PM_{10} and $PM_{2.5}$ levels in the indoor station were about 0.70 and 0.53 times those outdoors, respectively. The PM levels in the indoor station and outdoors were strongly correlated, suggesting that PM levels at the station concourse in the Taipei main station are significantly influenced by outdoor ambient PM levels. Moreover, the $PM_{2.5}$-to-PM_{10} ratios are significantly different among different subway systems. The low $PM_{2.5}$-to-PM_{10} ratio at the station concourse in the Taipei main station was found, and it was lower than that on the station platform.

REFERENCES

Aarnio, P., Yli-Tuomi, T., Kousa, A., Mäkelä T., Hirsikko, A., Hämeri, K., Päisänen, M., Hillamo, R., Koskentalo, T. and Jantunen, M. (2005). The Concentrations and Composition of and Exposure to Fine Particles ($PM_{2.5}$) in the Helsinki Subway System. *Atmos. Environ.* 39: 5059-5066.

Adams, H.S., Nieuwenhuijsen, M.J., Colvile, R.N., McMullen, M.A.S. and Khandelwal, P. (2001). Fine Particle ($PM_{2.5}$) Personal Exposure Levels in Transport Microenvironments, London, UK. *Sci. Total Environ.* 279: 29-44.

Braniš, M. (2006). The Contribution of Ambient Sources to Particulate Pollution in Spaces and Trains of the Prague Underground Transport System. *Atmos. Environ.* 40: 348-356.

Chan, L.Y., Lau, W.L., Lee, S.C. and Chan, C.Y. (2002a). Commuter Exposure to Particulate Matter in Public Transportation Modes in Hong Kong. *Atmos. Environ.* 36: 3363-3373.

Chan, L.Y., Lau, W.L., Zou, S.C., Cao, Z.X. and Lai, S.C. (2002b). Exposure Level of Carbon Monoxide and Respirable Suspended Particulate in Public Transportation Modes While Commuting in Urban Area of Guangzhou, China. *Atmos. Environ.* 36: 5831-5840.

Cheng, Y.H. (2008). Comparison of the TSI Model 8520 and Grimm Series 1.108 Portable Aerosol Instruments Used to Monitor Particulate Matter in an Iron Foundry. *J. Occup. Environ. Hyg.* 5: 157-168.

Cheng, Y.H., Lin, Y.L. and Liu, C.C. (2008). Levels of PM_{10} and $PM_{2.5}$ in Taipei Rapid Transit System. *Atmos. Environ.* 42: 7242-7249.

Duhme, H., Weiland, S.K. and Keil, U. (1998). Epidemiological Analyses of the Relationship between Environmental Pollution and Asthma. *Toxicol. Lett.* 102-103: 307-316.

Fromme, H., Oddoy, A., Piloty, M., Krause, M. and Lahrz, T. (1998). Polycyclic Aromatic Hydrocarbons (PHA) and Diesel Engine Emission (Elemental Carbon) Inside a Car and a Subway Train. *Sci. Total Environ.* 217: 165-173.

Gómez-Perales, J.E., Colvile, R.N., Fernández-Bremauntz, A.A., Gutiérrez-Avedoy, V., Páramo-Figueroa, V.H., Blanco-Jiménez, S., Bueno-López, E., Bernabé-Cabanillas, R., Mandujano, F., Hidalgo-Navarro, M. and Nieuwenhuijsen, M.J. (2007). Bus, Minibus, Metro Inter-Comparison of Commuters' Exposure to Air Pollution in Mexico City. *Atmos. Environ.* 41: 890-901.

Harrison, R.M., Jones, A.M. and Lawrence, R.G. (2004) Major Component Composition of PM_{10} and $PM_{2.5}$ from Roadside and Urban Background Sites. *Atmos. Environ.* 38: 4531-4538.

Hinds, W.C. (1999). *Aerosol Technology: Properties, Behavior, and Measurement of Airborne Particles*. 2nd ed., Wiley, New York.

Horvath, H., Kasahara, M. and Pesava, P. (1996). The Size Distribution and Composition of the Atmospheric Aerosol at a Rural and Nearby Urban Location. *J. Aerosol Sci.* 27: 417-435.

Johansson, C. and Johansson, P.Å. (2003). Particulate Matter in the Underground of Stockholm. *Atmos. Environ.* 37: 3-9.

Karlsson, H.L., Nilsson, L. and Möller, L. (2005). Subway Particles are More Genotoxic than Street Particles and Induce Oxidative Stress in Cultured Human Lung Cells. *Chem. Res. Toxicol.* 18: 19-23.

Kim, K.Y., Kim, Y.S., Roh, Y. M, Lee, C.M. and Kim, C.N. (2008). Spatial Distribution of Particulate Matter (PM_{10} and $PM_{2.5}$) in Seoul Metropolitan Subway Stations. *J. Hazard. Mater.* 154: 440-443.

Li, T.T., Bai, Y.H., Liu, Z.R. and Li, J.L. (2007). In-Train Air Quality Assessment of the Railway Transit System in Beijing: a Note. *Transport. Res. Part D-Transport. Environ.* 12: 64-67.

Osrt, B. and Chestnut, L. (1998). Assessing the Health Benefits of Reducing Particulate Matter Air Pollution in the United States. *Environ. Res.* 76: 94-106.

Park, D.U. and Ha, K.C. (2008). Characteristics of PM_{10}, $PM_{2.5}$, CO_2 and CO Monitored in Interiors and Platforms of Subway Train in Seoul, Korea. *Environ. Int.* 34: 629-634.

Pfeifer, G.D., Harrison, R.M. and Lynam, D.R. (1999). Personal Exposure to Airborne Metals in London Taxi Drivers and Office Workers in 1995 and 1996. *Sci. Total Environ.* 235: 253-260.

Pope III, C.A., Burnett, R.T., Thurston, G.D., Thun, M.J., Calle, E.E., Krewski, D. and Godleski, J.J. (2004). Cardiovascular Mortality and Long-Term Exposure to Particulate Air Pollution: Epidemiological Evidence of General Pathophysiological Pathways of Disease. *Circulation.* 109: 71-77.

Pope III, C.A., Burnett, R.T., Thun, M.J., Calle, E.E., Krewski, D., Ito, K. and Thurston, G.D. (2002). Lung Cancer, Cardiopulmonary Mortality, and Long-Term Exposure to Fine Particulate Air Pollution. *J. Am. Med. Assoc.* 287:1132-1141.

Ripanucci, G., Grana, M., Vicentini, L., Magrini, A. and Bergamaschi, A. (2006). Dust in the Underground Railway Tunnels of an ItalianTown. *J. Occup. Environ. Hyg.* 3: 16-25.

Salma, I., Weidinger, T. and Maenhaut, W. (2007). Time-Resolved Mass Concentration, Composition and Sources of Aerosol Particles in a Metropolitan Underground Railway sStation. *Atmos. Environ.* 41: 8391-8405.

Seaton, A., Cherrie, J., Dennekamp, M., Donaldson, K., Hurley, J.F. and Tran, C.L. (2005). The London Underground: Dust and Hazards to Health. *Occup. Environ. Med.* 62: 355-362

Sillanpää, M., Saarikoski, S., Hillamo, R., Pennanen, A., Makkonen, U., Spolnik, Z., Grieken, R.V., Koskentalo, T. and Salonen, R.O. (2005). Chemical Composition, Mass Size Distribution and Source Analysis of Long-Range Transported Wildfire Smokes in Helsinki. *Sci. Total Environ.* 350: 119-135.

Sitzmann, B., Kendall, M., Watt, J. and Williams, I. (1999). Characterisation of Airborne Particles in London by Computer-Controlled Scanning Electron Microscopy. *Sci. Total Environ.* 241: 63-73.

Yin, J. and Harrison, R.M. (2008). Pragmatic Mass Closure Study for $PM_{1.0}$, $PM_{2.5}$ and PM_{10} at Roadside, Urban Background and Rural Sites. *Atmos. Environ.* 42: 980-988.

Received for review, May 25, 2009
Accepted, July 27, 2009