Asian Journal of Atmospheric Environment
Vol. 7-1, pp.38-47, March 2013
doi: http://dx.doi.org/10.5572/ajae.2013.7.1.038

The Effect of Platform Screen Doors on PM_{10} Levels in a Subway Station and a Trial to Reduce PM_{10} in Tunnels

Youn-Suk Son[1,2), Amgad Salama[2), Hye-Seon Jeong[3), Suhyang Kim[3), Jin-Ho Jeong[2), Jaihyo Lee[4), Young Sunwoo[2,3) and Jo-Chun Kim[2,3),*]

[1)]Exposure, Epidemiology, and Risk Program, Department of Environmental Health, Harvard School of Public Health, Boston, Massachusetts, USA
[2)]Department of Environmental Engineering, Konkuk University, 1 Hwayang-dong, Gwangjin-Gu, Seoul 143-701, Korea
[3)]Department of Advanced Technology Fusion, Konkuk University, 1 Hwayang-dong, Gwangjin-Gu, Seoul 143-701, Korea
[4)]Department of Mechanical Engineering, Konkuk University, 1 Hwayang-dong, Gwangjin-Gu, Seoul 143-701, Korea

*Corresponding author. Tel: +82-2-450-4009, Fax: +82-455-2994, E-mail: jckim@konkuk.ac.kr

ABSTRACT

PM_{10} concentrations were measured at four monitoring sites at the Daechaung station of the Seoul subway. The four locations included two tunnels, a platform, and a waiting room. The outside site of the subway was also monitored for comparison purposes. In addition, the effect of the platform screen doors (PSDs) recently installed to isolate the PM_{10} in a platform from a tunnel were evaluated, and a comparison between PM_{10} levels during rush and non-rush hours was performed. It was observed that PM_{10} levels in the tunnels were generally higher than those in the other locations. This might be associated with the generation of PM_{10} within the tunnel due to the train braking and wear of the subway lines with the motion of the trains, which promotes the mixing and suspension of particulate matter. During this tunnel study, it was observed that the particle size of PM_{10} ranged from 1.8 to 5.6 μm. It was revealed that the PM_{10} levels in the tunnels were significantly increased by the PSDs, while those in the platform and waiting room decreased. As a result, in order to estimate the effect of ventilation system on PM_{10} levels in the tunnels, fans with inverters were operated. It was found that the concentration of PM_{10} was below 150 $\mu g/m^3$ when the air flow rate into a tunnel was approximately 210,000-216,000 CMH.

Keywords: Particulate matter, Subway, Platform screen door, Tunnel, Ventilation system

1. INTRODUCTION

The metropolitan city of Seoul uses more energy than other areas in South Korea due to its high population density. It also produces high emissions of air pollutants. Since an individual usually spends most of their working hours indoors, environmental air quality is directly related to indoor air quality (IAQ). Especially, the American Environmental Protection Agency (EPA) reported that in the United States the mean daily residential time spent in indoor areas was 21 hrs, and in Germany, the GerES II asserted that this duration was 20 hr. IAQ has been recognized as a significant factor in the determination of health and welfare (Sohn *et al*., 2008). In Korea, the Ministry of the Environment enforced the IAQ act to control five major pollutants in indoor environments. Of these, the IAQ standard for PM_{10} concentration was set to 150 $\mu g/m^3$ to protect public health. However, among the various types of indoor environments, underground subway stations have especially unique features. The confined space occupied by the underground subway system can promote the concentration of pollutants entering from the outside atmosphere in addition to those generated within the system. Therefore, it is expected that the subway system in the Seoul metropolitan area contains different species of hazardous pollutants due to old ventilation and accessory systems (Son *et al*., 2011; Kim *et al*., 2008). This expectation was confirmed in previous studies conducted at the Seoul subway stations. Park and Ha (2008) reported that the PM_{10} levels inside train lines 1, 2, and 4 exceeded the IAQ standard of 150 $\mu g/m^3$, while Choi *et al*. (2004) found that the mean PM_{10} concentration of the subway station was 182.9 $\mu g/m^3$, and Sohn *et al*. (2008) reported that the mean concentrations (PM_{10}-24 hr) on the platform and in the waiting room were 156 and 111 $\mu g/m^3$ for 35 sampling sites during the summer and winter seasons, respectively. The level of PM_{10} in some areas of the underground subway stations exceeded the 24-h national IAQ standard of South Korea (Kim *et al*., 2008). In

Table 1. Comparison of particulate matter (PM) concentrations in subway stations from various studies.

Study	Location	Particle size	Sampling site	Concentration (μg/m³)
Pfeifer *et al.*, 1999	London, UK	$PM_{2.5}$	Underground	246 (±52)
Seaton *et al.*, 2005	London, UK	$PM_{2.5}$	Station platform Inner subway	270-480 130-200
		PM_{10}	Station platform Inner subway	1000-1500
Priest *et al.*, 1998	London, UK	PM_9	Inner subway	795 (500-1000)
Sitzmann *et al.*, 1999	London, UK	PM_5	trains and on platforms	801
Aarnio *et al.*, 2005	Helsinki, Finmland	$PM_{2.5}$	Underground Ground Inner subway	47 (±4) and 60 (±18) 19 (±6) 21 (±4) 60 (23-103)
Kim *et al.*, 2008	Seoul, Korea	$PM_{2.5}$	Ground and Underground	48.9-126.8 115.2-135.7 81.6-176.3
		PM_{10}		122.6-310.1 28.68-356.6 237.8-480.1
Kim *et al.*, 2012	Seoul, Korea	PM_{10}	Platform	116 (76-164)
		$PM_{2.5}$		66 (39-129)
Park and Ha, 2008	Seoul, Korea	PM_{10}	Underground stations and Ground stations	123±6.6-145.3±12.8
		$PM_{2.5}$	Underground stations and Ground stations	105.4±14.4-121.7±16.1
Adams *et al.*, 2001	London, UK	$PM_{2.5}$	Underground Ground Underground	247.2 (105.3-371.2) 29.3 (12.1-42.3) 157.3 (12.2-263.5)
Fromme *et al.*, 1998	Berlin, Germany	PM_{10}	Summer Winter	153 (S.D.=22.0) 141 (S.D.=17.0)
Johansson and Johansson, 2003 Karlsson *et al.*, 2005	Stockholm, Sweden	$PM_{2.5}$	Platform	165-258 (34-388)
		PM_{10}		302-469 (59-722) 357
Braniš, 2006	Prague, Czech	PM_{10}	Underground	103
Salma *et al.*, 2007	Budapest, Hungary	PM_{10}	Underground Underground	155 (25-322) 180 (85-234)
		$PM_{2.5}$	Underground	
Grass *et al.*, 2010	New York, USA	$PM_{2.5}$	Underground	56±95
Onat and Stakeeva, 2012	Istanbul, Turkey	$PM_{2.5}$	Underground	49.3-181.7
Ripanucci *et al.*, 2006	Rome, Rome	PM_{10}	Underground	407 (71-877)
Awad, 2002	Cairo	PM_{35}	Ground and Underground	794-1096 (938.3±124)
Cheng *et al.*, 2008	Taipei	PM_{10}	Platform/Inside train	11-137/10-97
		$PM_{2.5}$		7-100/8-68
Li *et al.*, 2007	Bejing, China	TSP PM_{10} $PM_{2.5}$ PM_1	Underground Inner subway	456.2±176.7 324.8±125.5 112.6±42.7 38.2±13.9
		TSP PM_{10} $PM_{2.5}$ PM_1	Ground inner subway	166±78.7 108±56.0 36.9±18.7 14.7±6.6

fact, a higher level of particulate matter in underground subways, globally, was found compared to that in outdoor environments (Table 1).

It was also reported that the subway air particles were approximately eight times more genotoxic and four times more likely to cause oxidative stress in lung cells (Karlsson *et al.*, 2005). These substances are commonly generated from abrasion between the rail line, wheel, and brake interfaces (Kim *et al.*, 2012; Kang *et al.*, 2008).

Recently, platform screen doors (PSDs) have been installed and operated in many subway systems in Korea to prevent the diffusion of air pollutions into subway stations and secure the safety of the public. Some previous works reported that the PM concentration in subway stations after the PSDs installation was significantly reduced (Kim *et al.*, 2012; Jung *et al.*, 2010). However, they suggest that the PM concentration in a tunnel should be much higher due to the interruption of particle diffusion into subway stations by the PSDs. Moreover, most of the ventilation fans might not be in a normal condition because of their deterioration and high running cost; therefore, the PM concentrations in tunnels must have been high for a long period of time.

In this study, in order to investigate the effects of the PSDs system on PM_{10} levels, PM_{10} concentrations in the platform and waiting room are measured and compared with those inside tunnels. Furthermore, fans with inverters are operated within the ranges of 0-432,000 CMH and variations of PM_{10} concentrations are measured in order to estimate the effect of a ventilation system on PM_{10} concentrations in tunnels. In addition, particle size distribution analysis should be carried out to determine the characteristics of PM generated in tunnels.

2. EXPERIMENTAL

2.1 Measurement Sites and Periods

The Seoul subway system is serviced by lines 1 to 9 and accounts for more than 34.1% of the transportation services in the metropolitan city of Seoul. According to statistics provided by the Seoul Metro Transportation Center, approximately six million people in Seoul use the subway on a daily basis (http://www.seoulmetro.co.kr).

The PSDs (full-height barriers between the station floor and ceiling) were installed to prevent the mixing of air between the platform and tunnels, and to save energy and provide better indoor air quality. However, there is a concern that PM concentrations in the tunnel could be increased in the long run. In this work, PM_{10} concentrations were measured at four different sites in the Deacheong station (line 3) from August to September, 2010, to study the effects of the PSDs on Indoor air quality (IAQ). Fig. 1 shows the locations of the PM_{10} monitoring sites in this station. The four sampling locations included the waiting room, the platform, and two inside tunnels (between Irwon and Daecheong station and between Daecheong and Hangnyeoul station). All measurements were conducted at 1.5 m above ground level. Each site was monitored by continuous

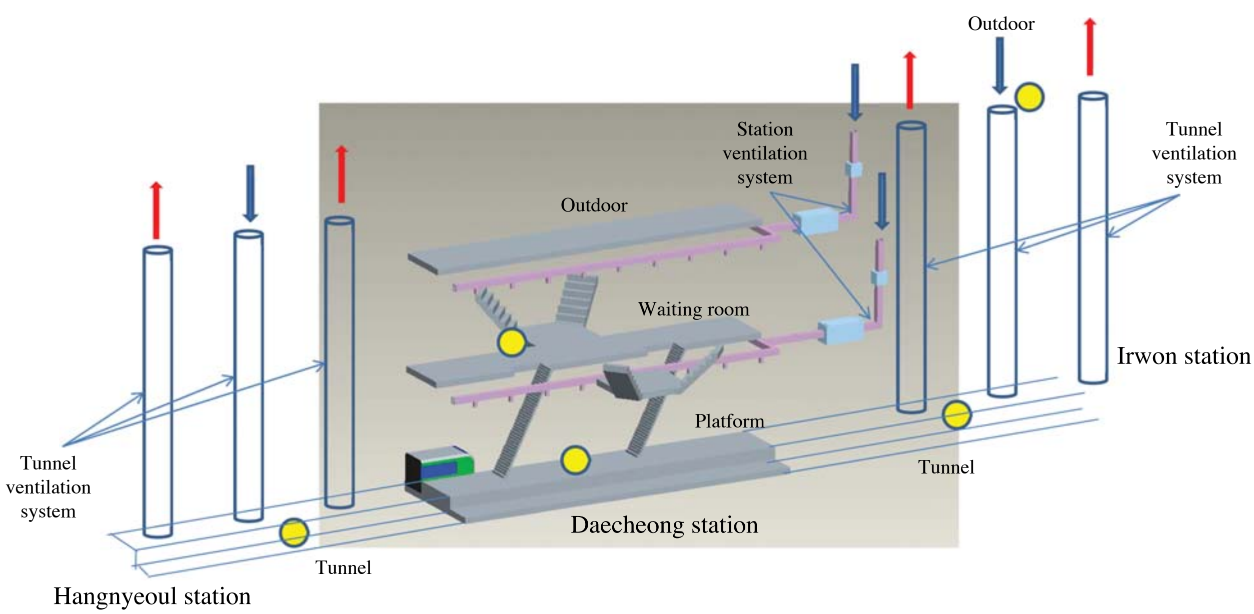

Fig. 1. Locations of the sampling sites (numbering circle: sampling site of each location; ↑ : air exhaust; ↓ : air inlet).

Table 2. Operating conditions of tunnel ventilation fans according to the three different modes.

Mode	Experimental period (Month/Day/Year - Hour : Minute)	Operating conditions (CMH)
I	08/25/2010-06:00 - 08/27/2010-00:00	Full operating fan: (Inlet : 420,000, Outlet : 432,000)
II	08/28/2010-06:00 - 09/02/2010-00:00	Half operating fan (Inlet : 210,000, Outlet : 216,000)
III	09/02/2010-06:00 - 09/06/2010-00:00	Fan off (Inlet : 0, Outlet : 0)

monitoring instruments. To carry out a comparison of PM_{10} levels in the underground subway station, an outdoor monitoring site was located about 600 m from the Deacheong station. Outdoor sampling was conducted at the air sampling inlet located approximately 1.5 m above the ventilation opening.

Generally, the mechanical ventilation system in subway tunnels is composed of one inlet and two outlet openings as shown Fig. 1. Three fans were installed in each opening. The general operating method of these fans allows for two fans to be run for ventilation while one fan is stopped for maintenance. In order to observe the PM_{10} concentration reduction and determine the efficient operating conditions, these fans were adjusted according to the three different modes as shown in Table 2.

2. 2 Sampling Equipment and Quality Assurance

In this study, particulate matter was continuously measured using a particulate monitor (KN-610, Kemik Corporation, Korea). The KN-610 is an automatic air monitor with a PM_{10} inlet head based on beta attenuation, which is a method certified by the Korean Ministry of the Environment as an effective approach for environmental testing. The sampling flow rate of the KN-610 was 16.7 L/min, and the hourly mean PM_{10} levels were measured. During field monitoring, the KN-610 was calibrated with the zero and span plates. The KN-610 was equipped with a moisture dryer to eliminate water vapor entering the filter. Furthermore, the concentration data of particulate matters was continuously collected at five different locations every hour using an RS232 (recommended standard 232) communication network.

In order to investigate particle size distribution in tunnels, a Micro Orifice Uniform Deposit Impactor (MOUDI 110, MSP Corp., U.S.A) was used. The MOUDI consisted of nine plates, a pressure gauge, and a vacuum pump. The air flow rates of this instrument were 30 L/min. Mass concentrations of PM in nine size ranges (0.18-0.32, 0.32-0.56, 0.56-1.0, 1.0-1.8, 1.8-3.2, 3.2-5.6, 5.6-10.0, 10.0-18.0 and >10 μm) were measured with Teflon filters for 20 h (Pore-size 2.0 μm, Zefluor filter, PALL corp., U.S.A). Filters were conditioned in a desiccator (AS1-001-01 LH type As one, Japan) for 72 h before weighing using a semi-micro-balance (R200D, Sartorius, Germany) with a resolution of 10 μg.

3. RESULTS AND DISCUSSION

3. 1 The Effect of PSDs on PM_{10} Levels in a Subway Station

Table 3 shows the mean PM_{10} concentrations, standard deviations, ranges, and medians at the four different measuring locations in Daecheong station and the single outdoor site. Experimental results show that PM_{10} levels ranged between 8 and 535 μg/m^3 inside the subway system (mean 87.75 μg/m^3) and between 4 and 401 μg/m^3 outside the station (mean 44 μg/m^3). Analytical results showed that PM_{10} concentrations in the Irwon tunnel ranked the highest, with a range of 9 -535 μg/m^3 (mean 177 μg/m^3), while those in the waiting room were the lowest, ranging between 9-114 μg/m^3 (mean 30 μg/m^3). This showed the pattern of PM increase in the order as follows: waiting room, platform, ambient air, tunnel. This trend differed somewhat from previous measurements (Jung *et al.*, 2010; Sohn *et al.*, 2008) which showed an increasing concentration pattern in the order as follows: ambient air, waiting room, platform, tunnel. This shift in the pattern may be attributed to the newly installed PSDs which isolate the tunnel from the platform. This trend was apparent when PM_{10} concentrations were compared during rush and non-rush hours, as discussed in section 3.3.

Moreover, the PM_{10} concentrations in the Irwon tunnel (mean 177 μg/m^3) were higher than those in the Hangnyeoul tunnel (mean 111 μg/m^3), which may be attributed to the effect of the ventilation system. One of the two inflow air fans at the Irwon tunnel was broken, resulting in higher PM_{10} concentrations.

Chemical analysis of the different elements contributing to PM in the subway system have shown that

Table 3. Average PM_{10} concentrations in different environments of Daecheong station (μg/m^3).

	Sampling periods	n	Mean	SD	Range	Median
Ambient	08/19/2010 - 09/09/2010	401	44	33	397 (4-401)	35
Waiting Room	08/31/2010 - 09/12/2010	201	30	14	105 (9-114)	27
Platform	08/20/2010 - 09/15/2010	555	33	18	115 (8-123)	30
Hangnyeoul Tunnel	08/25/2010 - 09/14/2010	314	111	74	329 (10-339)	96
Irwon Tunnel	08/14/2010 - 09/14/2010	716	177	113	526 (9-535)	150

Table 4. Average PM_{10} concentrations in different environments during rush and non-rush hours (μg/m^3).

	Rush hour					Non-rush hour					Two-tailed test p-value
	n	Mean	SD	Range	Median	n	Mean	SD	Range	Median	
Ambient	102	53	38	150 (4-154)	44	299	41	31	392 (9-401)	41	0.003
Waiting Room	46	29	10	43 (12-55)	27	155	30	15	105 (9-114)	26	0.47
Platform	148	36	19	85 (9-94)	35	407	31	18	115 (8-123)	28	0.006
Tunnel Hangnyeoul	83	154	86	319 (20-339)	140	231	96	63	313 (10-323)	86	<0.001
Tunnel Irwon	187	242	116	524 (11-535)	233	529	154	102	468 (9-477)	133	<0.001

Fe was the element with the highest concentration, and this became a key to determine the emission sources of particulate matter (Jung *et al.*, 2012, 2010). As determined by Johansson and Johansson (2003) and Nieuwenhuijsen *et al.* (2007), Fe generally originates from the wear of steel caused by friction between the wheels and rail, the wear of brakes, and the vaporization of metals. Therefore, it could be inferred that the concentrations of PM_{10} would be lower in sampling locations further from the tunnels.

3.2 Comparison of PM Levels during Rush and Non-rush Hours

During rush hours (7-9 AM and 5-7 PM), more trains per hour are operated in the Seoul subway system. Therefore, PM_{10} concentrations in the different locations are expected to reflect this pattern. Table 4 shows the average PM_{10} levels at the five locations during the rush and non-rush hours. Statistical results suggest that PM_{10} levels during the rush and non-rush hours significantly differ in the two tunnels (with ratios of PM_{10} during rush hour to non-rush hour at approximately 1.6 at both tunnels, p-value <0.001), less significantly differ in the ambient air (ratio of 1.3), and do not significantly differ at either the waiting room or the platform (ratios of 1 and 1.16, respectively). During rush hours, higher concentrations of PM_{10} were measured in the tunnels. Likewise, during rush hours, higher concentrations of PM_{10} were present in the ambient outdoor environment because of the high traffic loading. PM_{10} concentrations at both the platform and the waiting room, however, showed approximately some difference between rush and non-rush hours. This may be attributed to the effects of the platform screen doors which isolated the tunnels from the platform. Again, the difference in PM_{10} levels in the two tunnels reflected the effect of broken fans in the fresh air supply system at the Irwon tunnel.

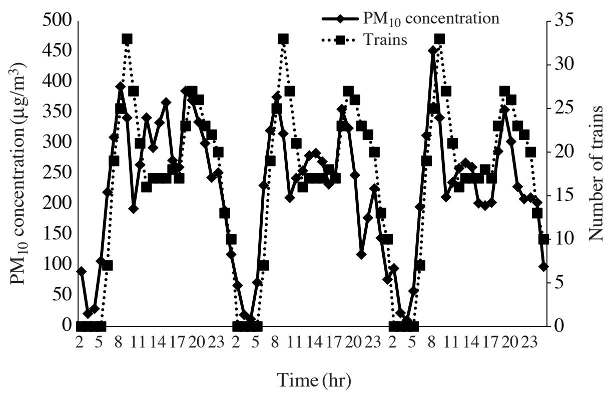

Fig. 2. Comparison of train frequency and PM_{10} concentration in tunnels.

Fig. 2 shows the relationship between train frequency and PM_{10} concentration. Train frequency is the average number of trains passing through the station per hour (in both directions). The train frequency reached maximum levels during the hours of 07:00-09:00 AM and 05:00-07:00 PM. Morning peaks were higher than evening, indicating higher traffic flow during this time period. The figure shows that PM_{10} concentrations at the Irwon tunnel followed almost the same trend as those of train frequency, which is in agreement with the results of previous research (Birenzvige *et al.*, 2003). This indicated that the train was the major source of particulate matter in the tunnel.

Table 5. Ratios of PM_{10} levels in different indoor locations with respect to the outdoor levels (μg/m^3).

	n	Mean	Median	Indoor PM_{10}/ Outdoor PM_{10}	Rperson	Two-tailed test p-value
Ambient	401	44	35	1	1	0
Waiting Room	201	30	27	0.68	−0.086	0.42
Platform	555	33	29.5	0.74	0.456	< 0.001
Hangnyeoul Tunnel	314	111	96	2.54	−0.002	0.979
Irwon Tunnel	716	177	150.5	4.03	0.52	< 0.001

3. 3 Comparison of PM_{10} Levels in Indoor and Outdoor Environments

Table 5 shows a comparison of PM_{10} levels between indoor and outdoor air. As the statistical analysis suggests, PM_{10} levels in the two tunnels were significantly higher than that in the outdoor air. This may be because of the generation of particulate matter in the tunnels due to abrasion and wear caused during the motion of the subway trains as well as to the braking systems. PM_{10} levels in the platform and in the waiting room were lower than the outdoor PM_{10} level, possibly because of the filtration by the ventilation system. Statistical analysis indicated positive correlation coefficients between the outdoor levels of PM_{10} and those at the platform and the Irwon tunnel, which were 0.456 and 0.52 (p-value < 0.001), respectively. Both inlet ventilation holes leading to the platform and the Irwon tunnel were located near a road with heavy traffic. This suggests that the indoor PM_{10} level increases when the outdoor PM_{10} levels increase, and vice versa. It has been reported that PM levels in the metro system were significantly influenced by outdoor ambient PM levels (Kim *et al.*, 2012; Cheng *et al.*, 2008; Braniš, 2006; Aarnio *et al.*, 2005). Furthermore, Cheng *et al.* (2008) suggested that PM_{10} levels in indoor and outdoor areas are positively correlated (0.53-0.91). Jung *et al.* (2010) indicated that PM_{10} concentrations in platforms generally increased as those in outdoor areas increased.

However, at both the waiting room and the Hangnyeoul tunnel, statistical analysis suggested that no correlation existed. To explain this trend for the Hangnyeoul tunnel, we need to consider that the outdoor measuring site was closer to the Irwon tunnel and was approximately 1 km farther from the measurement station at the Hangnyeoul tunnel. Also, the ventilation system at the Hangnyeoul tunnel is located near the river bank, which may have resulted in the poor correlation suggested by the statistical analysis.

3. 4 Variations of PM_{10} Concentrations and Size Distributions According to Fan Operating Conditions in a Tunnel

The fan used to control IAQ in the tunnels has been insufficiently run due to the high electrical cost and common complaints of fan noise. However, by not operating the fan, not only the exchange of air flow but also the natural ventilation itself has been interrupted. Also, the PSDs installed on the platform obstructed the air diffusion. The air in the tunnels has consequently increasingly deteriorated.

Fig. 3 shows the PM_{10} concentrations with respect to fan operating conditions in the Irwon tunnel during the study period. PM_{10} concentrations in Modes I, II, and III were 108.2 ± 44.1, 152.7 ± 82.5, and 316.1 ± 114.5 μg/m^3, respectively. On the other hand, PM_{10} concentrations measured in ambient air were 31.0 ± 16.4, 27.1 ± 13.8, and 55.5 ± 28.2 μg/m^3, respectively during those periods. It was suggested that PM_{10} concentrations in the tunnel should decrease as inlet and outlet air flow rates increase. From the result of the t-test, the PM_{10} concentration in ambient air did not significantly differ between modes I and II ($p > 0.05$). However, it was found that the PM_{10} concentration in the tunnels differed somewhat between modes I and II ($p < 0.05$).

Furthermore, PM_{10} concentrations in the tunnels reached approximately 150 μg/m^3 with appropriate fan operation. This study therefore showed that in order to reduce the PM concentration and increase energy efficiency, the fan needed to be utilized for the optimum operating condition.

Fig. 3. Variations of PM_{10} concentrations with respect to operating conditions of fans in the Irwon tunnel during the study period (straight line refers to PM_{10} concentration in the tunnel; dotted line refers to PM_{10} concentration in ambient air).

Even though many researchers have carried out studies to measure the PM concentrations on platforms and trains in the subway, the particle size distribution in the tunnels has been seldom investigated. In the results of some studies, particle size distribution in the underground subway (platforms and waiting rooms) was measured using a light-scattering technology. However, these results were possibly underestimated or overestimated with regard to some PM sizes (Cheng and Lin, 2010; Bachoual *et al.*, 2007; Furuya *et al.*, 2001) because the particles in the tunnel were generated from material abrasion such as wheels, brakes, and the overhead traction line, and their major component was Fe (Aarnio *et al*., 2005; Furuya *et al*., 2001). Christensson *et al*. (2002) estimated that 15% of the PM_{10} mass originated from brakes in the Stockholm subway. It has also been shown that Fe comprises from 41.8% to 61% of the total elemental composition (Bachoual *et al*., 2007). However, preferentially, light-scattering technology measures the number of particles per unit volume of air. The amount of concentration of PM is converted into a mass concentration via mathematical extrapolation with a correction factor (Cheng and Lin, 2010). The correction factor is a function of density. In previous studies, this correction factor was applied as 1.0 for all sized particles. This shows that PM mass concentration of some sized particles was underestimated or overestimated compared to actual mass concentration in the underground subway system, because these values did not reflect Fe density.

In order to solve this problem, gravimetric analysis for PM size distribution was conducted in this study. Table 6 shows mean and mass percentages of particle size distributions in the tunnels during modes II and III. The highest and second-highest mass concentration of particle size fractions at the Irwon tunnel were in the ranges of 3.2-5.6 μm (mean 40.8 μg/m^3; 29.0%) and 1.8-3.2 μm (mean 30.0 μg/m^3; 21.3%) during mode II, respectively. A similar occupied percentage in mass concentrations was obtained during mode III, and these were in the ranges of 1.8-3.2 μm (mean 67.0 μg/m^3; 27.8%) and 3.2-5.6 μm (mean 66.0 μg/m^3; 27.4%). This trend showed a significantly different pattern from that in the ambient air. In general, particle size distributions in the ambient air showed a bimodal pattern (e.g. 0.08-0.61 μm and 4.9-10.0 μm (Mazquiarán and Pinedo, 2007); 0.43-2.1 μm and 9.0-10.0 μm (Duan *et al*., 2007); 0.4-0.7 μm and 4.7-5.7 μm (Hien *et al*., 2007);

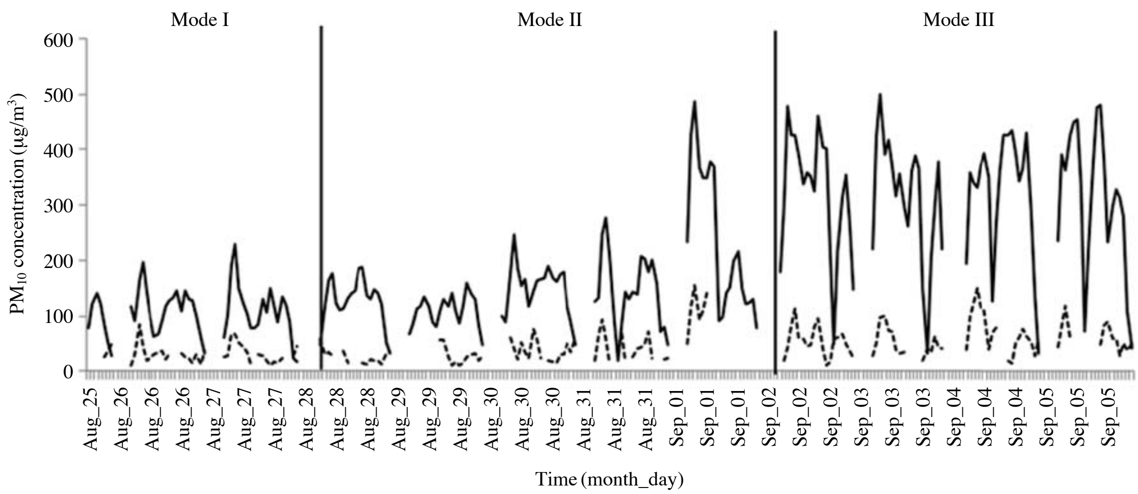

Fig. 3. Variations of PM_{10} concentrations with respect to operating conditions of fans in the Irwon tunnel during the study period (straight line refers to PM_{10} concentration in the tunnel; dotted line refers to PM_{10} concentration in ambient air).

Table 6. Size distributions of particle mass concentrations corrected during Modes II and III.

Size (μm)	Mode II			Mode III			Mode II/ Mode III percentage ratios
	Mean (μg/m^3)	SD (μg/m^3)	Percentage (%)	Mean (μg/m^3)	SD (μg/m^3)	Percentage (%)	
0.18-0.32	2.7	0.9	1.9	3.8	2.3	1.6	1.2
0.32-0.56	2.6	1.2	1.8	5.9	0.7	2.5	0.8
0.56-1.0	6.0	1.5	4.2	12.5	3.3	5.2	0.8
1.0-1.8	23.2	6.9	16.5	48.5	4.9	20.1	0.8
1.8-3.2	30.0	11.2	21.3	67.0	5.9	27.8	0.8
3.2-5.6	40.8	12.8	29.0	66.0	6.8	27.4	1.1
5.6-10.0	16.8	1.9	11.9	18.6	1.3	7.7	1.5
10.0-18.0	11.1	1.2	7.9	12.7	1.0	5.3	1.5
18.0-30.0	7.5	1.9	5.3	5.7	1.5	2.4	2.2
Total	140.6	30.4	100.0	240.8	13.3	100.0	1.0

0.95-1.5 μm and 3.0-7.5 μm (Chrysikou *et al*., 2009). Lee *et al*. (2008) also showed that the PM_{10} size distribution should be bimodal with the peaks in the 0.65-1.1 μm and 4.7-5.8 μm size ranges, respectively, in Seoul urban areas. Furthermore, Chrysikou and Samara (2009) showed that the mean PM concentration was obtained in the particle fraction <0.95 μm, accounting for 62% and 36% of total PM in an urban site in Greece during winter and summer. A bimodal distribution is evident with two peaks at the fine and the coarse size range.

The results of this work show that Mode II/Mode III percentage ratios of particle mass concentration were increased in the particle size ranges of 0.18-0.32 and 5.6-30.0 as the inlet and outlet air flow rates increased. It was found that the shape of PM_{10} size distribution in the tunnels changed the bimodal pattern, such as that in the ambient air, when the amount of ventilation flow increased. This result suggests that the particle size distribution range from 1.8 to 5.6 μm was possibly due to the movement of trains. Furaya *et al*. (2001) noted that the concentrations of suspended particulate matter in the size range of 0.5-5.0 mm were higher at the platform in the subway stations than above ground.

However, in previous studies, the mass size distribution at the tunnel in Irwon station differed from that at the concourse. Cheng and Lin (2010) found that the main mass concentrations of particle fractions at the concourse in Taipei main station were in the range of 10-20 μm (39.76%). 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.

4. CONCLUSIONS

To compare concentrations of particular matter according to sampling sites, sampling was carried out using a beta attenuation method at four different sites at the Deachaung station and at one outdoor site. The measured PM_{10} concentrations in the tunnels were approximately 2-7 times higher than those at the other sites. In general, the further the sampling locations were from the tunnels, the lower were the concentrations of PM_{10}. However, concentrations of particulate matter in the waiting room and the platform were lower than those in the ambient air, possibly due to the newly installed platform screen doors. It was confirmed from this work that the platform screen doors significantly affected the indoor air quality in the subway system. This study also showed that the hourly PM_{10} concentration in tunnels generally followed the same hourly trend as train frequency. In addition, it was found that a particle size range from 1.8 to 5.6 μm appeared through the run of trains. Furthermore, it was revealed that, with appropriate fan operation, a PM_{10} concentration below 150 $\mu g/m^3$ was obtained in the tunnels. This suggests that the appropriate ventilation method should be applied to the subway to obtain both PM reduction and energy saving.

ACKNOWLEDGEMENT

This work was supported by the Seoul R&BD Program (CS070160) and the Korea Ministry of Education as “The Second Stage of BK 21 Project”. This work was also supported by the Hi Seoul Science (Humanities) Fellowship from Seoul Scholarship Foundation.

REFERENCES

Aarnio, P., Yli-Tuomi, T., Kousa, A., Mäkelä, T., Hirsikko, A., Hämeri, K., Päisänen, M., Hillamo, R., Koskentalo, T., Jantunen, M. (2005) The concentrations and composition of and exposure to fine particles ($PM_{2.5}$) in the Helsinki subway system. Atmospheric Environment 39, 5059-5066.

Adams, H.S., Nieuwenhuijsen, M.J., Colvile, R.N., McMullen, M.A.S., Khandelwal, P. (2001) Fine particle ($PM_{2.5}$) personal exposure levels in transport microenvironments, London, UK. Science of Total Environment 279, 29-44.

Awad, A.H.A. (2002) Environmental study in subway metro stations in Cairo, Egypt. Journal of Occupational Health 44, 112-118.

Bachoual, R., Boczkowski, J., Goven, D., Amara, N., Tabet, L., On, D., Leçon-Malas, V., Aubier, M., Lanone, S. (2007) The concentrations and composition of and exposure to fine particles ($PM_{2.5}$) in the Helsinki subway system. Chemical Research in Toxicology 20(10), 1426-1433.

Birenzvige, A., Eversole, H., Seaver, M., Francesconi, S., Valdes, E., Kulaga, H. (2003) Aerosol characteristics in a subway environment. Aerosol Science and Technology 37, 210-220.

Braniš, M. (2006) The concentration of ambient sources to particulate pollution in spaces and trains of the Prague underground transport system. Atmospheric Environment 40, 348-356.

Cheng, Y.H., Lin, Y.L. (2010) Measurement of Particle Mass Concentrations and Size Distributions in an Underground Station. Aerosol and Air Quality Research 10, 22-29.

Cheng, Y.H., Lin, Y.L., Liu, C.C. (2008) Level of PM_{10} and $PM_{2.5}$ in Taipei rapid transit system. Atmospheric Environment 42, 7242-7249.

Choi, H.W., Hwang, I.J., Kim, S.D., Kim, D.S. (2004) Determination of source contribution based on aerosol number and mass concentration in Seoul subway stations. Journal of Korea Society for Atmospheric Environment 20, 17-31 (in Korean with English abstract).

Christensson, B., Sternbeck, J., Ancker, K. (2002) Luftburna partiklaräpartikelhalter, elementsammansättning och emissionskällor. SL Infrateknik AB (Airborne particles-particle concentrations, elemental composition and emission sources, In Swedish).

Chrysikou, L.P., Samara, C.A. (2009) Seasonal variation of the size distribution of urban particulate matter and associated organic pollutants in the ambient air. Atmospheric Environment 43, 4557-4569.

Chrysikou, L.P., Gemenetzis, P.G., Samara, C.A. (2009) Winter time size distribution of polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs) and organochlorine pesticides (OCPs) in the urban environment: street-vs rooftop-level measurements. Atmospheric Environment 43, 290-300.

Duan, J., Xi, B., Tan, J., Sheng, G., Fu, J. (2007) Seasonal variation on size distribution and concentration of PAHs in Guangzhou city, China. Chemosphere 67, 614-622.

Fromme, H., Oddoy, A., Piloty, M., Krause, M., Lahrz, T. (1998) Polycyclic aromatic hydrocarbons (PHA) and diesel engine emission (elemental carbon) inside a car and a subway train. Science of Total Environment 217, 165-173.

Furuya, K., Kudo, Y., Okinaga, K., Yamuki, M., Takahashi, S., Araki, Y., Hisamatsu, Y. (2001) Seasonal variation and their characterization of suspended particulate matter in the air of subway stations. Journal of Trace and Microprobe Techniques 19(4), 469-485.

Grass, D.S., Ross, J.M., Family, F., Barbour, J., Simpson, H.J., Coulibaly, D., Hernandez, J., Chen, Y., Slavkovich, V., Li, Y., Graziano, J., Santella, R.M., Brandt-Rauf, P., Chillrud, S.N. (2010) Airborne particulate metals in the New York City subway: A pilot study to assess the potential for health impacts. Environmental Research 110, 1-11.

Hien, T.T., Thanh, L.T., Kameda, T., Takenaka, N., Bandow, H. (2007) Distribution characteristics of polycyclic aromatic hydrocarbons with particle size in urban aerosols at the roadside in Ho Chi Minh City, Vietnam. Atmospheric Environment 41, 1575-1586.

Johansson, C., Johansson, P.Å. (2003) Particulate matter in the underground of Stockholm. Atmospheric Environment 37, 3-9.

Jung, H.J., Kim, B., Ryu, J., Maskey, S., Kim, J.C., Sohn, J., Ro, C.-U. (2010) Source identification of particulate matter collected at underground subway stations in Seoul, Korea using quantitative single-particle analysis. Atmospheric Environment 44, 2287-2293.

Jung, H.J., Kim, B., Malek, M.A., Koo, Y.S., Jung, J.H., Son, Y.S., Kim, J.C., Kim, H., Ro, C.-U. (2012) Chemical speciation of size-segregated floor dusts and airborne magnetic particles collected at underground subway stations in Seoul, Korea. Journal of Hazardous Material 213-214, 331-340.

Kang, S., Hwang, H., Park, Y., Kim, H., Ro, C.-U. (2008) Chemical compositions of subway particles in Seoul, Korea determined by a quantitative single particle analysis. Environmental Science and Technology 42, 9051-9057.

Karlsson, H.L., Nilsson, L., Möller, L. (2005) Subway particles are more genotoxic than street particles and induce oxidative stress in cultured human lung cells. Chemical Research in Toxicology 18, 19-23.

Kim, K.H., Ho, D.X., Jeon, J.S., Kim, J.C. (2012) A noticeable shift in particulate matter levels after platform screen door installation in a Korean subway station. Atmospheric Environment 49, 219-223.

Kim, K.Y., Kim, Y.S., Roh, Y.M., Lee, C.M., Kim, C.N. (2008) Spatial distribution of particulate matter (PM_{10} and $PM_{2.5}$) in Seoul metropolitan subway station. Journal of Hazardous Material 154, 440-443.

Lee, J.Y., Shin, H.J., Bae, S.Y., Kim, Y.P., Kang, C.H. (2008) Seasonal variation of particle size distributions of PAHs at Seoul, Korea. Air Quality, Atmosphere and Health 1, 57-68.

Li, T.T., Bai, Y.H., Liu, Z.R., Li, J.L. (2007) In-train air quality assessment of the railway transit system in Beijing: a note. Transportation Research Part D 12, 64-67.

Mazquiarán, M.A.B., Pinedo, L.C.O.d. (2007) Organic composition of atmospheric urban aerosol: variations and sources of aliphatic and polycyclic aromatic hydrocarbons. Atmospheric Research 85, 288-299.

Nieuwenhuijsen, M.J., Gómez-Perrales, J.E., Colvile, R.N. (2007) Levels of particulate air pollution, its elemental composition, determinants and health effects in metro systems. Atmospheric Environment 41, 7995-8006.

Onat, B., Stakeeva, B. (2012) Assessment of fine particulate matters in the subway system of Istanbul. Indoor and Built Environment. Published online.

Park, D.U., 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. Environment International 34(5), 629-634.

Pfeifer, G.D., Harrison, R.M., Lynam, D.R. (1999) Personal exposures to airborne metals in London taxi drivers and office workers in 1995 and 1996. Science of Total Environment 235(1-3), 253-260.

Priest, D., Burns, G., Gorbunov, B. (1998) Dust levels on the London Underground: a health hazard to commuters?, http://62.164.135.147/feat/feat0017.htm.

Ripanucci, G., Grana, M., Vicentini, L., Magrini, A., Bergamaschi, A. (2006) Dust in the underground railway tunnels of an Italian town. Journal of Occupational and Environmental Hygiene 3, 16-25.

Salma, I., Weidinger, T., Maenhaut, W. (2007) Time-resolved mass concentration, composition and sources of aerosol particles in a metropolitan underground railway station. Atmospheric Environment 41, 8391-8405.

Seaton, A., Cherrie, J., Dennekamp, M., Donaldson, K., Hurley, J.F., Tran, C.L. (2005) The London underground: dust and hazards to health. Occupational and Environmental Medicine 62, 355-362.

Sitzmann, B., Kendall, M., Watt, J., Williams, I. (1999)

Characterisation of airborne particles in London by computer-controlled scanning electron microscopy. Science of Total Environment 241, 63-73.
Sohn, J.R., Kim, J.C., Kim, M.Y., Son, Y.S., Sunwoo, Y. (2008) Particulate behavior in subway airspace. Asian Journal of Atmospheric Environment 2(1), 54-59.
Son, Y.S., Kang, Y.H., Chung, S.G., Park, H.J., Kim, J.C. (2011) Efficiency evaluation of adsorbents for the removal of VOC and NO_2 in an underground subway station. Asian Journal of Atmospheric Environment 5(2), 113-120.

(Received 29 October 2012, revised 28 January 2013, accepted 30 January 2013)