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

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**ABSTRACT**

PM$_{10}$ concentrations were measured at four monitoring sites at the Daechuang 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 μg/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 μg/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 μg/m$^3$, while Choi et al. (2004) found that the mean PM$_{10}$ concentration of the subway station was 182.9 μg/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 μg/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).
| Study               | Location          | Particle size | Sampling site                  | Concentration (µg/m³) |
|--------------------|-------------------|---------------|--------------------------------|-----------------------|
| Pfeifer et al., 1999 | London, UK        | PM₂.₅         | Underground                    | 246 (± 52)            |
| Seaton et al., 2005 | London, UK        | PM₂.₅         | Station platform                | 270-480               |
|                    |                   | PM₁₀          | Inner subway                   | 130-200               |
|                    |                   | PM₁₀          | Station platform                | 1000-1500             |
| Priest et al., 1998 | London, UK        | PM₉           | Inner subway                   | 795 (500-1000)        |
| Sitzmann et al., 1999 | London, UK       | PM₅           | trains and on platforms        | 801                   |
| Aarnio et al., 2005 | Helsinki, Finmland | PM₂.₅         | Underground                    | 47 (± 4) and 60 (± 18) |
|                    |                   |               | Ground                         | 19 (± 6)              |
|                    |                   |               | Inner subway                   | 21 (± 4)              |
|                    |                   |               |                                | 60 (23-103)           |
| Kim et al., 2008   | Seoul, Korea      | PM₂.₅         | Ground and Underground         | 48.9-126.8            |
|                    |                   | PM₁₀          |                                | 115.2-135.7           |
|                    |                   |               |                                | 81.6-176.3            |
|                    |                   | PM₁₀          |                                | 122.6-310.1           |
|                    |                   |               |                                | 28.68-356.6           |
|                    |                   |               |                                | 237.8-480.1           |
| Kim et al., 2012   | Seoul, Korea      | PM₁₀          | Platform                       | 116 (76-164)          |
|                    |                   | PM₂.₅         |                                | 66 (39-129)           |
| Park and Ha, 2008  | Seoul, Korea      | PM₁₀          | Underground stations and       | 123 ± 6.6-145.3 ± 12.8|
|                    |                   | PM₂.₅         | Ground stations                |                       |
| Adams et al., 2001 | London, UK        | PM₂.₅         | Underground                    | 247.2 (105.3-371.2)   |
|                    |                   |               | Ground                         | 29.3 (12.1-42.3)      |
|                    |                   |               | Underground                    | 157.3 (12.2-263.5)    |
| Fromme et al., 1998| Berlin, Germany   | PM₁₀          | Summer                         | 153 (S.D. =22.0)      |
|                    |                   |               | Winter                         | 141 (S.D. =17.0)      |
| Johansson and       | Stockholm, Sweden | PM₂.₅         | Platform                       | 165-258 (34-388)      |
| Johansson, 2003     |                   | PM₁₀          |                                | 302-469 (59-722)      |
| Karlsson et al., 2005|                 |               |                                | 357                   |
| Braniš, 2006        | Prague, Czech     | PM₁₀          | Underground                    | 103                   |
| Salma et al., 2007  | Budapest, Hungary | PM₁₀          | Underground                    | 155 (25-322)          |
|                    |                   | PM₂.₅         |                                | 180 (85-234)          |
| Grass et al., 2010  | New York, USA     | PM₂.₅         | Underground                    | 56±95                 |
| Onat and Stakeeva, 2012 | Istanbul, Turkey | PM₂.₅         | Underground                    | 49.3-181.7            |
| Rippa et al., 2006  | Rome, Italy       | PM₁₀          | Underground                    | 407 (71-877)          |
| Awad, 2002          | Cairo             | PM₃₅          | Ground and Underground         | 794-1096 (938.3 ± 124)|
| Cheng et al., 2008  | Taipei            | PM₁₀          | Platform/Inside train          | 11-137/10-97          |
|                    |                   | PM₂.₅         |                                | 7-100/8-68            |
| Li et al., 2007     | Beijing, China    | TSP           | Underground                    | 456.2 ± 176.7         |
|                    |                   | PM₁₀          |                                | 324.8 ± 125.5         |
|                    |                   | PM₂.₅         |                                | 112.6 ± 42.7          |
|                    |                   | PM₁          |                                | 38.2 ± 13.9           |
|                    |                   | TSP           | Underground Inner subway       | 166 ± 78.7            |
|                    |                   | PM₁₀          |                                | 108 ± 56.0            |
|                    |                   | PM₂.₅         |                                | 36.9 ± 18.7           |
|                    |                   | PM₁          |                                | 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).
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.

### 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) |

### 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-microbalance (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...
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 shows the relationship between train frequency and PM$_{10}$ concentration in tunnels.

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

| Environment       | 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$^3$).

| Environment       | Rush hour       | Non-rush hour   | Two-tailed test p-value |
|-------------------|-----------------|-----------------|-------------------------|
|                   | n   | Mean | SD  | Range      | Median | n   | Mean | SD  | Range      | Median | p-value |
| 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   |
| Hangnyeoul Tunnel | 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  |

Fig. 2. Comparison of train frequency and PM$_{10}$ concentration in tunnels.
3.3 Comparison of PM\textsubscript{10} Levels in Indoor and Outdoor Environments

Table 5 shows a comparison of PM\textsubscript{10} levels between indoor and outdoor air. As the statistical analysis suggests, PM\textsubscript{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\textsubscript{10} levels in the platform and in the waiting room were lower than the outdoor PM\textsubscript{10} level, possibly because of the filtration by the ventilation system. Statistical analysis indicated positive correlation coefficients between the outdoor levels of PM\textsubscript{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\textsubscript{10} level increases when the outdoor PM\textsubscript{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\textsubscript{10} levels in indoor and outdoor areas are positively correlated (0.53-0.91). Jung et al. (2010) indicated that PM\textsubscript{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\textsubscript{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\textsubscript{10} concentrations with respect to fan operating conditions in the Irwon tunnel during the study period. PM\textsubscript{10} concentrations in Modes I, II, and III were 108.2 ± 44.1, 152.7 ± 82.5, and 316.1 ± 114.5 µg/m\textsuperscript{3}, respectively. On the other hand, PM\textsubscript{10} concentrations measured in ambient air were 31.0 ± 16.4, 27.1 ± 13.8, and 55.5 ± 28.2 µg/m\textsuperscript{3}, respectively during those periods. It was suggested that PM\textsubscript{10} concentrations in the tunnel should decrease as inlet and outlet air flow rates increase. From the result of the t-test, the PM\textsubscript{10} concentration in ambient air did not significantly differ between modes I and II (p > 0.05). However, it was found that the PM\textsubscript{10} concentration in the tunnels differed somewhat between modes I and II (p < 0.05).

Furthermore, PM\textsubscript{10} concentrations in the tunnels reached approximately 150 µg/m\textsuperscript{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\textsubscript{10} concentrations with respect to operating conditions of fans in the Irwon tunnel during the study period (straight line refers to PM\textsubscript{10} concentration in the tunnel; dotted line refers to PM\textsubscript{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 over-

| Table 5. Ratios of PM\textsubscript{10} levels in different indoor locations with respect to the outdoor levels (µg/m\textsuperscript{3}). |
|---|---|---|---|---|---|---|
| n | Mean | Median | Indoor PM\textsubscript{10}/Outdoor PM\textsubscript{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 |
head 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.

| Size (µm)  | Mode II | Mode III |
|------------|---------|----------|
|            | Mean (µg/m$^3$) | SD (µg/m$^3$) | Percentage (%) | Mean (µg/m$^3$) | SD (µg/m$^3$) | Percentage (%) | Mode II/Mode III percentage ratios |
| 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               |

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.
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 particulate 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 μg/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.

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