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[원 저]

Reduction of Particulate Matters Levels in Railway Cabins in Korea

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ABSTRACT

Objectives: High concentrations of airborne particulate matters (PM) can affect the health of passengers using public transportation. The objectives of this research were to develop a PM control system for a railway cabin and to evaluate the performance of the device under conditions of an actual journey.

Methods: This study measured the concentrations of PM_{10} and $PM_{2.5}$ simultaneously in a reference cabin and a cabin with the PM control device.

Results: The average PM_{10} concentration in the reference cabin was 100 μg/m^3, and the PM_{10} concentration in the cabin with the control device was 79 μg/m^3. While the overall control efficiency of the control device was 15.4%, reduction was more effective for peak PM_{10} concentration. However, $PM_{2.5}$ levels did not differ greatly between the reference cabin and the cabin with the control device. The ratio of $PM_{2.5}$ to PM_{10} was 0.37. PM_{10} concentrations in cabins were not associated with ambient concentrations, indicating that the main sources of PM_{10} were present in cabins. Additionally, average CO_2 concentration in the cabins was 1,359 ppm, less than the maximum of 2,000 ppm set out by the Korean Ministry of Environment's guideline. The CO_2 concentration in cabins was significantly associated with the number of passengers: the in-cabin concentration = 23.4 × N + 460.2, where N is the number of passengers.

Conclusions: Application of the PM control device can improve PM_{10} concentration, especially at peak levels but not $PM_{2.5}$ concentration.

Keywords: transportation, particulate matter, indoor air, train, control device for PM

I. Introduction

People are exposed to many microenvironments, but exposure can differ significantly. Americans spent 87% of their daily time indoors, 8% outdoors, and 5% of their time in various forms of transport (cars, buses, railroad, airplanes).[1] Koreans spend 59% and 67% of their time at home on weekdays and weekends, respectively, and about 7% of their time on public transportation.[2] In Korea, 9.1 billion people used bus transit in 2006, while about 970 million people and 2 billion people used railroads and subways, respectively.[3]

Although people may spend less than 10% of their day in a transportation environment, in-vehicle exposure can be a significant part of personal exposure to airborne particulate matter (PM).[4] PM levels in cars have been associated with the ambient level and surrounding traffic.[5] PM levels in vehicles can be higher than the ambient concentration.[6] PM_{10} concentrations inside buses and trams have exceeded the ambient level by 3-5 times in

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Munich, Germany.[6] High exposure during short transportation periods may have a greater effect on health than 24-h exposure.[7] Exposure to black carbon during school bus commuting can provide one-third of children's total daily exposure, even when bus commuting time only takes 10% of their day.[8]

PM levels in vehicles can be affected by various factors. PM_{10} levels are affected by the mode of transportation and the vehicle's ventilation system.[9] Wind speeds, route, and transportation mode (bicycle, bus, or car) are reportedly responsible for 35% of the variability of $PM_{2.5}$ exposure.[10] In-vehicle $PM_{2.5}$ levels are lower than roadside concentrations when a vehicle's air conditioning system is in operation due to deposition of particles on a filter associated with the recirculation of air in the vehicle.[11] Indoor air quality in train cabins has been associated with the location of air inlets in heating, ventilation, and air conditioning (HVAC) systems.[12] Smoking can be a significant source of PM, although all trains are now smoke-free in Korea. Thus, control of airborne particulate matter in vehicles has become important research issues for improving air qualities in public transportation.

Researchers have investigated indoor air pollution in various modes of transportation to identify the levels and sources of air pollutants, although few studies have focused on controlling indoor air pollution. Among the various modes of transportation in Hong Kong, railway and air-conditioned vehicles had lower PM exposure than non-air-conditioned vehicles.[9] Separation of smoking and non-smoking compartments is not effective, because poly aromatic hydrocarbons and PM_{10} were highly elevated in both smoking and non-smoking compartments.[13] The particle concentration in French TGV smoking vehicles was improved by the installation of an electric precipitation filter.[14] However, such reduction can also be readily achieved by implementing a smoke-free policy. To date, no reported study has focused on controlling indoor air quality in railway coaches.

The purposes of this research were to develop a PM control system for a railway cabin and to evaluate the performance of the device under conditions of an actual journey. The control device is called a Cyclone Particulate Matter Separator (CPS); it uses centrifugal force (with a novel shape of an axial-flow cyclone) and a roll filter. Additionally, we assessed carbon dioxide (CO_2) concentrations in the cabin.

II. Materials and Methods

To achieve high control efficiency, the test cabin was equipped with a CPS and a roll filter system. The CPS consists of a vortex separator panel, a fan, and a ducting assembly; Fig. 1 provides the working schematics. Centrifugal action in the cyclone separates the particles from the inlet air. The PM separation efficiency of the cyclone was 98.8%, when test particles of SAECTD (ISO 12103-1 A4 CTD) were supplied at 1 g/m^3. The cleaned air was then passed via the separator panel to the inlet of the air conditioning unit. Of the total inlet air contaminated with PM, 15% was vented to the atmosphere though the scavenge outlet duct and 85% of the air passed through the control device and was re-supplied to the cabin. The HVAC of the tested coach was located at the lower part of the cabin where the airborne particulates flow into the cabin. The flow rate of the inlet air at each cabin was set to 26 cubic meters per minute (CMM), consisting of 6 CMM (23%) fresh air and 20 CMM of recirculated air.

Fig. 2 presents the roll filter system, which consists of fans, a timer, and rolled filters. Filters were rolled up and placed inside the filter system.

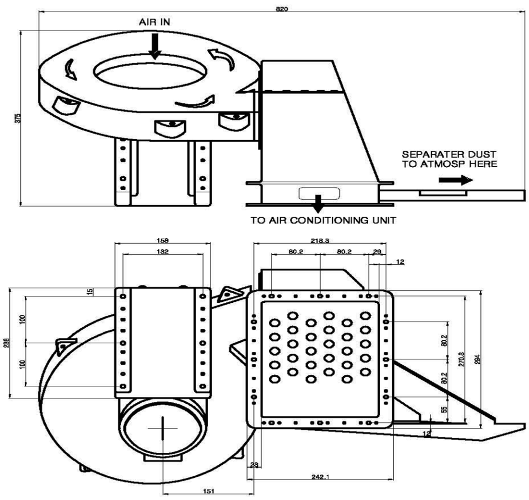

Fig. 1. Schematic diagram of the Cyclone Particulate Matter Separator (CPS).

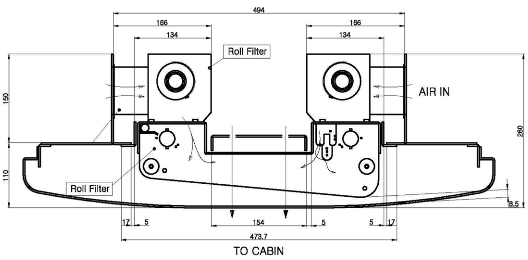

Fig. 2. Schematic diagram of the roll filter.

When the fan was running, return air came into the side of a filter and clean air was supplied into the cabin. The roll filter operated automatically at specific intervals according to a timer or pressure sensor. The roll filter consisted of electret nylon. When the electrostatic 68 mesh filter materials were mounted on the roll filter system, PM removal efficiency was 62.2%, with a maximum holding capacity of 321.8 g/m^2. The PM removal efficiency of the filter media was evaluated using ISO 12103 A2 standard particles.

To evaluate the PM control devices, one reference cabin and one cabin installed with the control devices were placed in line. Each cabin has its own HVAC unit. Although there is a door between railroad cars, the door was always closed. The reference cabin and control cabin were simultaneously measured. The cabin with the PM control devices was tested on a route between Pyeongtaek and Yeosu. This route is 262 km long and takes 4 h in the Yeosu-bound direction and 4 h 25 min in the Pyeongtaek-bound direction. The PM reduction performance test was repeated six times between February 14 and April 13, 2008. In addition, CO_2 concentrations in reference cabin were measured in a route between Suwon and Iksan. This route is 215 km long and takes 4 h 20 min. CO_2 measurements were repeated 20 times between February 14 and March 18, 2009. The measurement devices were placed in center of cabins with 1.2 m height.

The concentrations of $PM_{10}$and $PM_{2.5}$ were measured by a laser particle counter using a light scattering method (MetOne Model GT-331). This device was used to measure PM_{10} and $PM_{2.5}$ in cabins simultaneously at 5-min intervals. CO_2 concentration was measured using a nondispersive infrared multi-gas monitor (RAE Model PGM-54). Measurement devices were placed in the breathing zone of seated passengers. All measurements were calibrated according to the manufacturer's instruction to ensure data reliability. The collected PM and CO_2 measurement data were analyzed using a SPSS ver 12.0 (SPSS Institute), and the interaction of each measured contaminant (PM_{10}, $PM_{2.5}$, and CO_2) was verified by leveraging the correlation analysis.

III. Results and Discussion

Table 1 lists the PM_{10} and $PM_{2.5}$ levels in the reference and modified cabins. The average PM_{10} concentrations in reference cabin were 96±51 μg/m^3 and 104±44 μg/m^3 for the Pyeongtaek-Yeosu route and the Yeosu-Pyeongtaek route, respectively. The PM_{10} concentrations in reference cabins exceeded the Korean guideline of 150 μg/m^3 for public transportation in 13% and 19% of the samples for the Pyeongtaek-Yeosu route and the Yeosu-Pyeongtaek route, respectively. The average $PM_{2.5}$ concentrations in the reference cabin were 38±15 μg/m^3 and 36±10 μg/m^3 for the Pyeongtaek-Yeosu route and the Yeosu-Pyeongtaek route, respectively.

The average PM_{10} level for the modified cabin was 79 μg/m^3, significantly lower than the average

Table 1. Descriptive results for PM in the reference and modified cabins

			Cabins	
			Reference	Modified
PM_{10} (μg/m^2)	Pyeongtaek →Yeosu	n	49	49
		Mean	96	68
		Range	44~333	35~164
		S.D	51	23
	Yeosu → Pyeongtaek	n	54	54
		Mean	104	89
		Range	43~241	37~160
		S.D	44	27
	Average		100	79
$PM_{2.5}$ (μg/m^2)	Pyeongtaek → Yeosu	n	49	49
		Mean	38	35
		Range	18~106	18~74
		S.D	15	11
	Yeosu → Pyeongtaek	n	54	54
		Mean	36	41
		Range	18~60	16~74
		S.D	10	12
	Average		37	38

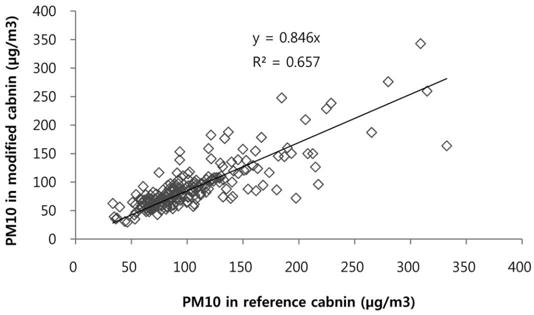

Fig. 3. Correlation of PM_{10} levels between the reference and modified cabins.

of 100 μg/m^3 for the reference cabin (paired t-test; p<0.001). Fig. 3 shows the association between PM_{10} levels in the reference and modified cabins. Installation of the PM reduction devices reduced PM_{10} concentration by 15.4% in the modified cabin. However, reduction rates were higher when PM_{10} concentrations were at peak levels. When PM_{10} concentrations in the modified cabin were higher than 150 μg/m^3, application of the PM control device resulted in an average reduction of 22%. PM_{10} concentrations in the reference and modified cabins exceeded the guideline level of 150 μg/m^3 in 13.7% and 8.5% of samples, respectively. $PM_{2.5}$ levels did not show a significant reduction. Average $PM_{2.5}$ concentrations in the modified cabin were 35±11 μg/m^3 and 41±12 μg/m^3 for the Pyeongtaek -Yeosu route and the Yeosu-Pyeongtaek route, respectively.

Application of CPS with the roll filter system effectively reduced relatively large particles in actual train, but not fine particles. However, the reduction rate of PM_{10} was not remarkable. Overall reduction was 15.4% and the rate was slightly higher to 22% when PM level was higher than guideline. Although the CPS with roll filter system can remove over 90% of particles, the situation in field may not provide sufficient dust collection to the control system. Considering various PM generation sources in train, better dust collection to the control system should be considered.

The measured PM_{10} levels in railway cabins were comparable to other published levels for subway cabins in Seoul. The PM_{10} concentration of 100 μg/m^3 was slightly lower than one published level of 144 μg/m^3 in Seoul subway cabins,[12] but comparison between two studies must consider measurement quality. We used a laser particle counter, for which monitoring is a strong function of particle size and refractive index. Thus, the results of the MetOne monitor were compared with those of a beta attenuation monitor (FH62 carbonium-14A, Anderson INS) in subway cabins. The MetOne monitor underestimated PM_{10} levels by 39%. Considering this underestimation, our results were similar to the levels found in subway stations. However, the levels in Korean trains were higher than the published levels for the Kowloon-Canton Railway (60 μg/m^3), mass transit railway (MTR; 44 μg/m^3), and light rail transit (LRT; 41 μg/m^3) in Hong Kong (Chan *et al.,* 2002). These results indicated that PM concentrations were affected by types of stations and routes (e.g., subway stations or roadside ambient air).

In the reference cabin, the ratio of $PM_{2.5}$ to PM_{10} was 0.37. This is significantly lower than the published ratio of 0.82 in a Seoul subway cabin.[12] The published $PM_{2.5}/PM_{10}$ ratios in Hong Kong were 0.75 in MTR, 0.83 in LRT and 0.62 in tram cabins.[9] Such variation in $PM_{2.5}/PM_{10}$ ratios may indicate differing particle sources between the railways used in this study and urban subways. In this study, the most common PM was coarse particles; potential sources may have included soil dust in rural areas and re-suspension of settled coarse particles in cabins. In contrast, transportation in urban settings may be affected by mobile air pollution sources and combustion of fossil fuels.

PM_{10} levels in cabins were not associated with the ambient air. Of the cities located along the railways routes, three had ambient air monitoring stations: Cheonan, Iksan, and Jeonju. No association was apparent between PM_{10} levels in cabins and ambient level. PM_{10} concentrations in cabins were significantly higher than the adjacent ambient PM_{10} levels ($p < 0.05$). The average ambient PM_{10} level was 113 μg/m^3, while PM_{10} levels in cabins were 195 μg/m^3 or 73% higher. Actual PM_{10} levels in cabins may have been even higher, because nephelometer measurements tend to underestimate. This supports the presence of indoor sources of PM_{10} in cabins, possibly re-suspension of coarse particles. In urban rail system of the Los Angeles Metro, in-cabin PM_{10} and $PM_{2.5}$ levels were strongly correlated with ambient concentrations.[15] This indicated presence of local emissions (vehicular

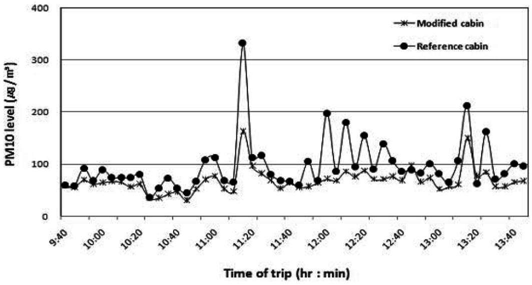

Fig. 4. Influence of the PM removal devices on PM_{10} levels in the reference and modified cabins.

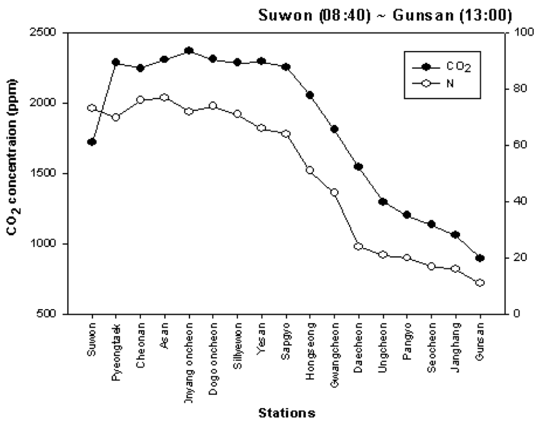

Fig. 5. Typical concentration profile according to the number of passengers in the reference cabin.

traffic and road dust) and common sources for PM_{10} and $PM_{2.5}$. The correlation was very weak in this study. The difference may be affected by train passing rural region, less frequent stop and operation of air conditioning.

In-cabin CO_2 concentrations were measured on the Suwon-Gunsan route, and the number of passengers was also counted; Fig. 5 presents the results. The average number of passengers was 38, 60% of the maximum capacity of 64 people. CO_2 concentration levels were significantly affected by thenumber of passengers. The number of passengers was counted at each station and matched with the corresponding CO_2 concentrations. For 388 readings, the average CO_2 concentration was 1285 ± 557 ppm. The Korean Ministry of the Environment recommends 2000 ppm of CO_2 as a maximum, according to the Indoor Air Quality Guidelines for Public Transportation. In-cabin CO_2 concentrations exceeded the guideline level in 10% of samples.

CO_2 concentrations in cabins were significantly associated with thenumber of passengers ($R^2 = 0.801$). Indoor CO_2 concentration levels increased by approximately 23.4 ppm for each additional passenger ($CO_2 = (23.4 \times N) + 460.2$). CO_2 concentrations exceeded 2,000 ppm when the number of passengers exceeded the standard capacity of 64 people. A high correlation between the number of passengers and CO_2 concentration was observed previously in the Beijing Ground Railway Transit System in Beijing, China ($R^2 = 0.807$).[16] Another study reported a slightly lower correlation between the number of passengers and CO_2 concentrations ($R^2 = 0.577$) in subway cabins, and reported that CO_2 concentration levels increased by approximately 10 ppm for each additional passenger ($CO_2 = (9.8 \times N) + 916.8$).[17]

IV. Conclusions

In this study, we analyzed PM and CO_2 concentrations in train cabins. While the average PM_{10} level in the reference cabin was 100 μg/m^3, the average PM_{10} concentration was 79 μg/m^3 (21% lower) in the cabin equipped with the PM control device. However, difference was not apparent in $PM_{2.5}$ concentrations between the reference and modified cabins.The $PM_{2.5}/PM_{10}$ ratio was 0.37, suggesting that most of the PM consisted of coarse particles. The lack of association between PM_{10} in cabins and ambient PM_{10} suggests that the main sources were present in the cabins. While CO_2 concentrations satisfied the Korean guideline of $< 2{,}000$ ppm, a significant correlation was observed between CO_2 concentration levels and the number of passengers. This study assessed the severity of indoor air quality in public railway transit and tested a PM control device to reduce the concentration of PM. The proposed PM control device may be useful for reduction of PM_{10} but not for $PM_{2.5}$ and such characteristics may limit application to other modes of public transit.

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