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Removal of Particulate Matter Emitted from a Subway Tunnel Using Magnetic Filters

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Supporting Information

ABSTRACT: We removed particulate matter (PM) emitted from a subway tunnel using magnetic filters. A magnetic filter system was installed on the top of a ventilation opening. Magnetic field density was increased by increasing the number of permanent magnet layers to determine PM removal characteristics. Moreover, the fan's frequency was adjusted from 30 to 60 Hz to investigate the effect of wind velocity on PM removal efficiency. As a result, PM removal efficiency increased as the number of magnetic filters or fan frequency increased. We obtained maximum removal efficiency of PM_{10} (52%), $PM_{2.5}$ (46%), and PM_1 (38%) at a 60 Hz fan frequency using double magnetic filters. We also found that the stability of the PM removal efficiency by the double filter (RSD, 3.2−5.8%) was higher than that by a single filter (10.9−24.5%) at all fan operating conditions.

INTRODUCTION

Indoor air quality has been recognized as a pivotal factor determining health and welfare.[1] Among the various types of indoor environments, underground subway stations have particularly unique features. The pollutant concentration will be increased due to the confined space occupied by an underground subway. In particular, higher levels of particulate matter (PM) have been reported in most underground subways worldwide, including those in London, Helsinki, Berlin, Stockholm, Rome, Cairo, Beijing, and Seoul.[2−16]

The PM contents emitted from a subway system include mainly iron-containing compounds such as magnetite (Fe_3O_4), hematite (α-Fe_2O_3), maghemite (γ-Fe_2O_3), and iron (Fe) metal, which adversely affect human health.[10,17−21] In our previous study, it was reported that iron compounds of subway particles were emitted originally as iron metal, being oxidized to magnetite due to its instantaneous high temperature by contact with air.[22] In Seoul subway systems, most aerosol particles in the tunnel and at the platform were iron-containing compounds (75−85% of relative abundance among total particles).[23] Another study reported that the dust comprised approximately 67% iron oxide by mass in the $PM_{2.5}$ samples.[4] Therefore, subway PM will adversely affect subway passengers and workers. Furthermore, Bigert et al. reported that diverse worker groups in subway systems may be exposed to considerably different PM levels depending on working places. It means that PM is not equally distributed throughout all parts of a subway system.[24] It has been reported that diverse particles emitted from underground subway systems have cytotoxic and inflammatory potential and transient biological effects, and its toxicity was attributed to the high iron compounds.[4,25−27] Karlsson et al. reported that subway particles are approximately eight times more genotoxic and four times more likely to cause oxidative stress in lung cells.[10] They also concluded that all particles from the metro cause DNA damage due to redox-active iron, which is mainly (60−70%) in the form of magnetite. On the other hand, in a few results of a previous human exposure study, there is little consistent evidence of actual adverse effects on subway passengers and workers.[24,28,29] Grass et al. reported that steel dust exposure at the individual level was not correlated with any of the measured biomarkers.[29] Bigert et al. also mentioned that they could not find any short-term effects, with respect to airway inflammation or lung function, of particle exposure in the subway employees.[24] Accordingly, further study should be conducted to clearly understand the adverse human effect of subway PM.

To prevent this effect, ventilation openings and platform screen doors (PSD) are installed and run. Most platforms in the Seoul subway system have PSDs installed to protect passengers and to improve air quality on the platform.[30] However, PM concentrations in the tunnel are higher than

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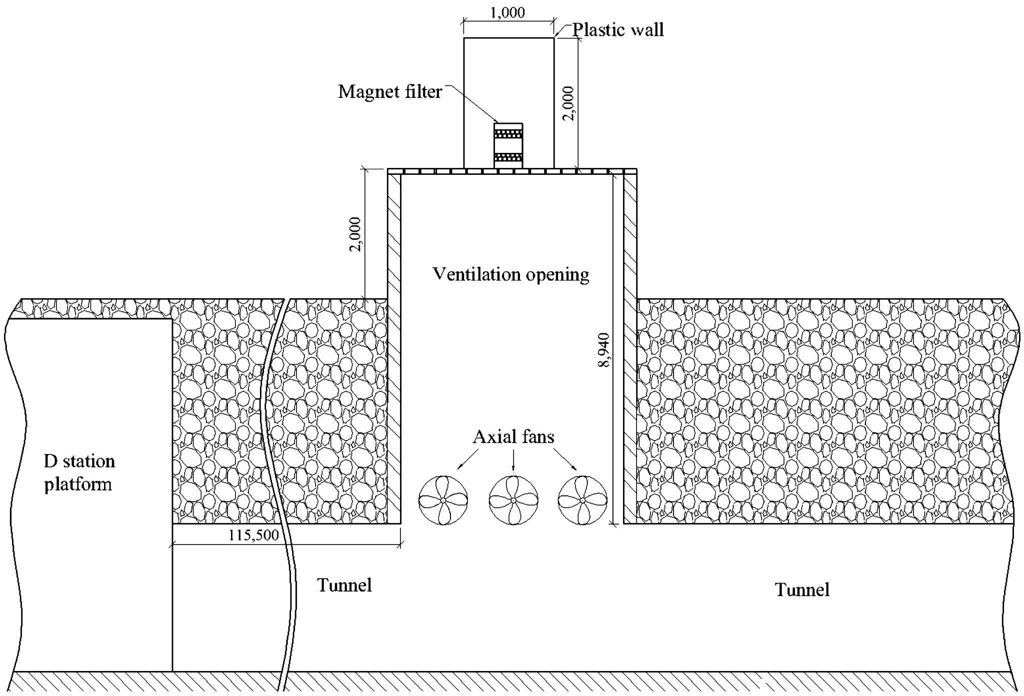

Figure 1. Detailed information of the ventilation system.

those on the platform.[16,30] In addition, ventilation systems could cause other problems. Air pollutants in the tunnel are emitted to ambient air, which will affect people living near ventilators as well as pedestrians on the street. Therefore, this problem is an important issue to be solved as soon as possible. There are many studies on separation by filters such as particle separation, ion exchange, and yeast filtration.[31] Thus, it is possible to remove iron oxide using magnets, as the PM emitted from subway tunnels consists mainly of iron in the form of magnetic particles (Fe_3O_4). Jung et al. studied chemical speciation of size-segregated floor dust and airborne magnetic particles collected in underground subway stations in Seoul, Korea.[18] They reported that the fraction of magnetic particles in the floor dust varied from 98% to 100% with particles < 25 μm in size. Jung et al. also reported that iron particle (2.5−10 μm in size) content varied from 77.3% to 86.9% in tunnel dust samples.[23] In our previous study using XRD analysis, the nonmagnetic hematite comprised significant portions (30%) of tunnel samples, which were collected at the same location as this study.[22] Nevertheless, most of the particles were attracted to the magnet, indicating a magnetic filter could be used to remove subway PM.

Therefore, the objective of this study is to investigate PM removal efficiency using magnetic filters with different strengths and various fan frequencies. Furthermore, we are going to confirm the possibility of preventing the transfer of PM emitted from the subway system. This is the first study to remove PM emitted from a subway tunnel using magnetic filters.

MATERIALS AND METHODS

Experiment. PM generated in the tunnels is emitted to ambient air based on the exchange rate of the ventilation system. The strength of the magnet field was based on the number of magnets. Therefore, PM removal efficiencies using a magnetic field filter in a subway system depend on ventilation exchange rate and magnetic field density. The frequencies of the fan system at the ventilation opening were varied from 30 to 60 Hz to investigate the effect of wind velocity on PM removal efficiency. The type of fan in ventilation openings was an axial one. Each flow capacity of an axial fan was 90 000 m^3/h, and three axial fans were generally installed in a ventilation opening. The ventilation opening used in this study was located above the tunnel to emit PM generated in the tunnel, and the distance between a platform of D station and the ventilation opening was 115.5 m (Figure 1). Then, the number of magnetic filters, such as single and double filters, was changed at the same wind velocity to compare removal efficiencies. The experiment testing the relationship between fan frequency and wind velocity was carried out, and r^2 was 0.99 (Figure 2). When the fan frequencies were increased from 30 to 60 Hz, the wind velocities were approximately increased from 1 to 2.2 m/s.

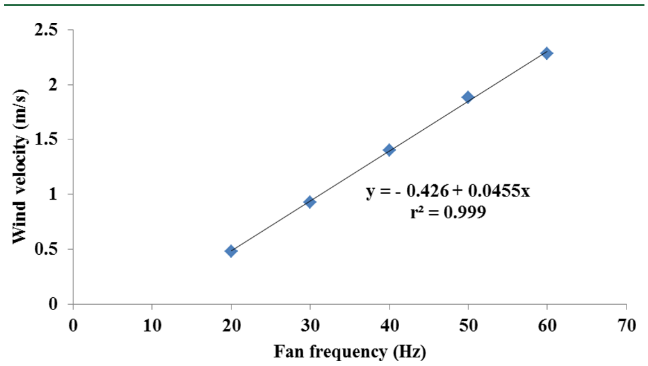

Figure 2. Relationship between fan frequency and wind velocity.

Magnetic Filters. The most popular system used to control movement of magnetic-based solids is a magnetically stabilized bed (MSB).[31] This system is often applied for a flue in a tube. In this study, self-developed magnetic filters were used to remove PM at the ventilation opening, which was larger than

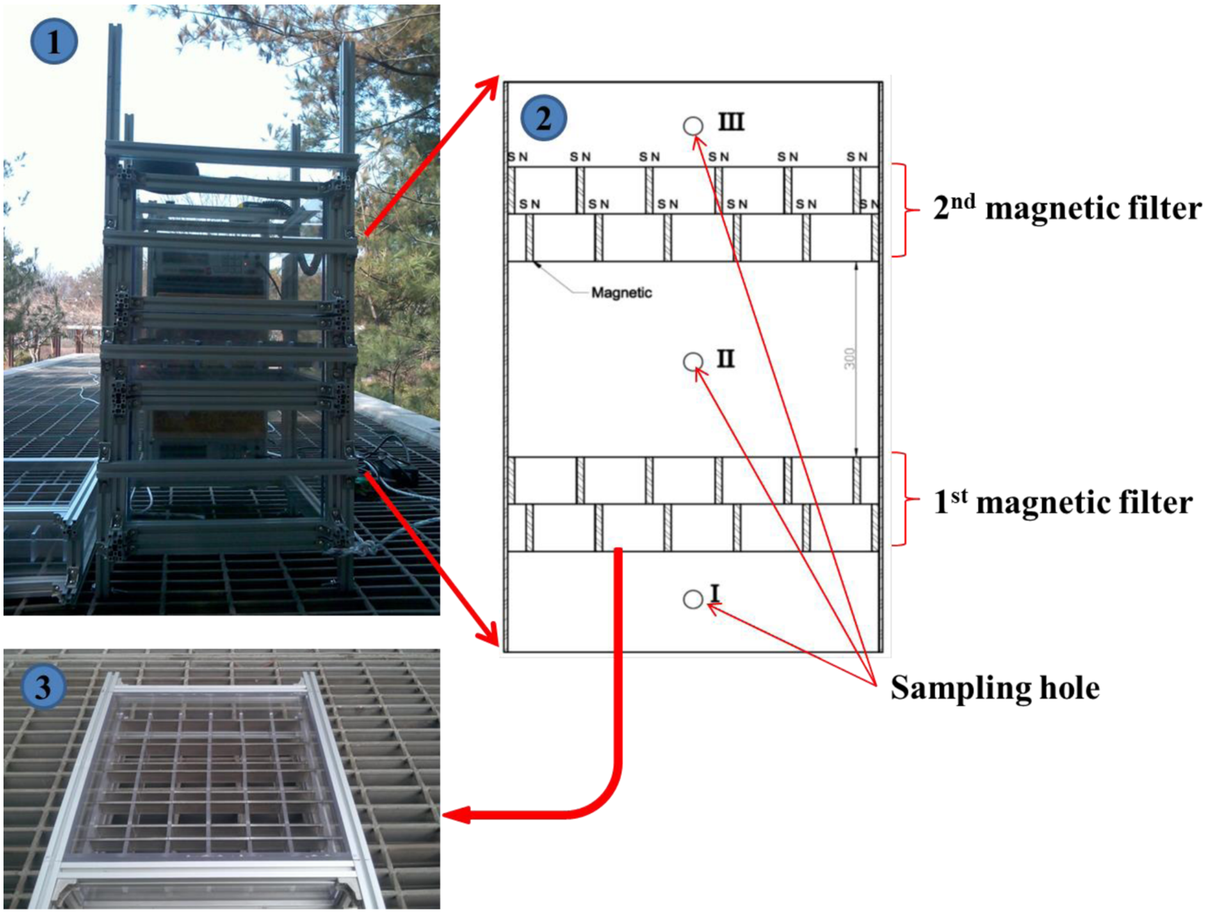

Figure 3. Magnetic filter system (S and N are polar of the magnet; (1) high-resolution picture of the magnetic filter system installed above an actual ventilation hole; (2) schematic of the magnetic filter system with two filter layers; (3) magnetic filter).

the tube. Because it was difficult to use a MSB, a magnetic filter net was designed like a comb.

A permanent magnet net was installed on the top of the ventilation opening at D Station, Seoul, Korea. On the basis of our previous study,[22] each magnetic filter was comprised of 12 separate magnets and two layers (Figure 3). The magnet's size was 100 × 25 × 5 mm (NdFeB-Magnet, Yuyang Magnetech Co., Ltd., South Korea). Every magnet had a field density of 2600 Gs. Twelve magnets were kept in a magnetic filter frame. The distance between magnets was 50 mm. The frame size was 300 × 100 × 50 mm. The magnetic field density of a single filter was 31 200 Gs, and the magnetic field density of a double filter was 62 400 Gs. The south and north poles of each magnet were arranged to face each other to create a magnetic field net. Two magnetic filter layers were installed in a box, and the distance between the two layers was 300 mm. To prevent dilution of PM by ambient air, the magnetic filter system was surrounded by a plastic wall (height and girth 2000 × 4000 mm). Magnetic filter intensity was adjusted by the number of filters in layers.

PM Measurements. Three portable aerosol spectrometers (model 1.108, GRIMM Aerosol Technik GmbH & Co. KG, Ainring, Germany) were simultaneously used at three positions to determine the PM concentrations (Figure 3). The instruments were placed before the magnetic filter (I), after the first magnetic filter (II), and after the second magnetic filter (III). The distances between each sampling site were approximately 350 mm, as shown in Figure 3. In general, the sampling efficiency of a portable aerosol spectrometer is changed by a wind velocity and sampling inlet type. To minimize this limitation, the same sampling inlets were applied to three portable aerosol spectrometers, and the wind velocities at three sampling sites were almost similar. The time for these experiments was overall 32 h. This study was conducted during subway run time. The frequencies of the train through an experimental area during this time were approximately 17–23/h. Besides, we tried to avoid peak time (rush hours 7–9 AM and 5–8 PM) to reduce an experimental variable. The experimental duration for each fan frequency was 4 h, and the experiment was duplicated. The PM measuring interval was configured to 6 s, and the sampling flow rate was 1.2 L/min. The size range of the particles was measured from 0.3 to 10 μm by 13 channels. Before the experiment for PM removal using the magnetic filter, calibrations among three portable aerosol spectrometers, which are installed at the same conditions to obtain the reliability of them, were carried out at every fan frequency (30, 40, and 60 Hz) without the magnetic filters to reduce measurement errors. The linear regression equations and coefficients of determination (r^2) are shown in Table S1, Supporting Information.

RESULTS AND DISCUSSION

PM Concentration. PM concentrations emitted from the tunnel were measured. PM concentrations at the point after the single and double magnetic filters during all experimental periods were also determined for comparison (Table 1). The

Table 1. PM Concentrations and Removal Efficiencies by the Filter Numbers[a]

	before filter		after single filter		after double filter		single filter	double filter
	mean (SD)	min−max	mean (SD)	min−max	mean (SD)	min−max	removal efficiency (%)	
PM_{10} ($\mu g/m^3$)	245.6 ± 43.9	70.6−363.7	192.6 ± 46.7	86.2−300.4	130.7 ± 26.8	58.7−205.2	21.6	46.8
$PM_{2.5}$ ($\mu g/m^3$)	219.1 ± 40.2	53.1−303.9	174.7 ± 40.9	57.6−249.0	128.6 ± 27.3	42.5−182.9	20.3	41.3
PM_1 ($\mu g/m^3$)	159.7 ± 38.4	35.6−217.1	135.5 ± 39.0	28.3−189.3	104.8 ± 28.8	26.5−145.9	15.2	34.4
$PM_{2.5}/PM_{10}$	0.89		0.91		0.98			
PM_1/PM_{10}	0.65		0.70		0.80			

[a]Note: These values were estimated over all fan frequencies.

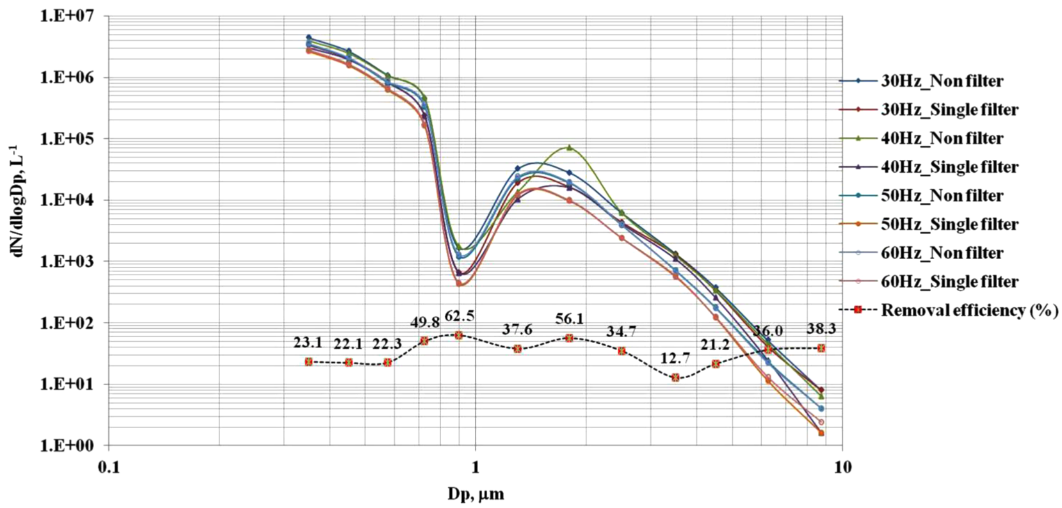

Figure 4. Variations of particle numbers and removal efficiencies by the particle size distribution.

concentration ranges of PM_{10}, $PM_{2.5}$, and PM_1 emitted from the tunnel were 70.6−363.7, 53.1−303.9, and 35.6−217.1 $\mu g/m^3$, respectively. These PM concentration ranges were similar to those of a previous study.[31] Son et al. reported that the range of PM_{10} concentrations in the same tunnel were 10−339 $\mu g/m^3$, which was very similar to our result.[16]

PM concentrations decreased as the number of filters increased. When the double filter was used, the average PM_{10} concentration was reduced to 130.7 $\mu g/m^3$. We found that the $PM_{2.5}/PM_{10}$ and PM_1/PM_{10} ratios increased as the number of filters increased. The $PM_{2.5}/PM_{10}$ ratio sampled before the magnetic filter was 0.89, and its value was similar to the result of a previous study, which concluded that $PM_{2.5}$ in the Seoul underground subway system is 80−90% PM_{10}.[15] However, the $PM_{2.5}/PM_{10}$ ratio measured after the double filter increased to 0.98, indicating that removal of coarse particles (size 2.5−10 μm) was easier than that of fine particles (<2.5 μm) when the number of filters was increased. Moreover, removal efficiency by the double filter was greater than that by the single filter.

Size Distribution by Particle Number. As shown in Figure 4, the main particle size emitted from the subway tunnel based on particle numbers was fine particles (<1.0 μm), which was similar with previous studies.[3,4,7,10−15] Seaton et al. reported that about 80% of particles emitted from a subway tunnel have diameters < 1 μm.[3] In addition, we observed that the number of initial particles emitted from the tunnel decreased with an increase in fan frequency, indicating that the concentration of PM emitted to ambient air through the ventilation system decreased with an increase in wind velocity. It also suggests that the PM concentration in the tunnel could rapidly decrease as fan frequency was increased. We found a similar result in our previous study.[16] Son et al. reported that PM_{10} concentrations in a tunnel should decrease as inlet and outlet air flow rates by the fan increase.

We assumed that the PM removal efficiency by the magnetic filters also depended on the kinetics of PM in wind. To determine the PM kinetics, we adjusted the fan frequency from 30 to 60 Hz and measured removal efficiencies with respect to wind velocity. The removal efficiencies of a single filter at 30, 40, and 60 Hz based on particle number were 26.8%, 39.6%, and 37.8%, respectively. Moreover, we found that the average removal efficiencies of particles ranging in size from 0.65 to 1.0 (49.8−62.5%) and from 1.6 to 2.0 μm (56.1%) were higher than those of sizes ranging from 0.3 to 0.65 μm (22.1−23.1%), 1.0 to 1.6 μm (37.6%), and 2.0 to 10 μm (12.7−38.3%). In terms of particle number, these results indicate that eliminating a particle size range (0.65−2.0 μm) among fine particles (<2.5 μm) is generally more efficient than that of coarse particles (2.5−10 μm) when magnetic filters are used to remove PM emitted from a tunnel. Many researchers have mentioned that health problems by fine particles (<2.5 μm) are higher than those by inhalable coarse particles (2.5−10 μm) on account of their greater surface area/volume ratio and potential to penetrate to the airways and alveoli of the lung.[32−35] Through the results of this study, the health problems by a portion of fine particles could be improved using the magnetic filter. However, more extensive studies such as the shape and strength of magnetic filter should be conducted in order to raise the removal efficiency for smaller particles (<0.65 μm).

Removal Efficiencies Based on PM Mass Concentration. Removal efficiencies of PM_{10}, $PM_{2.5}$, and PM_1 based on the PM mass concentration using single and double filters by passage of time are shown in Figure 5. We found that PM removal efficiency increased as the number of magnetic filters

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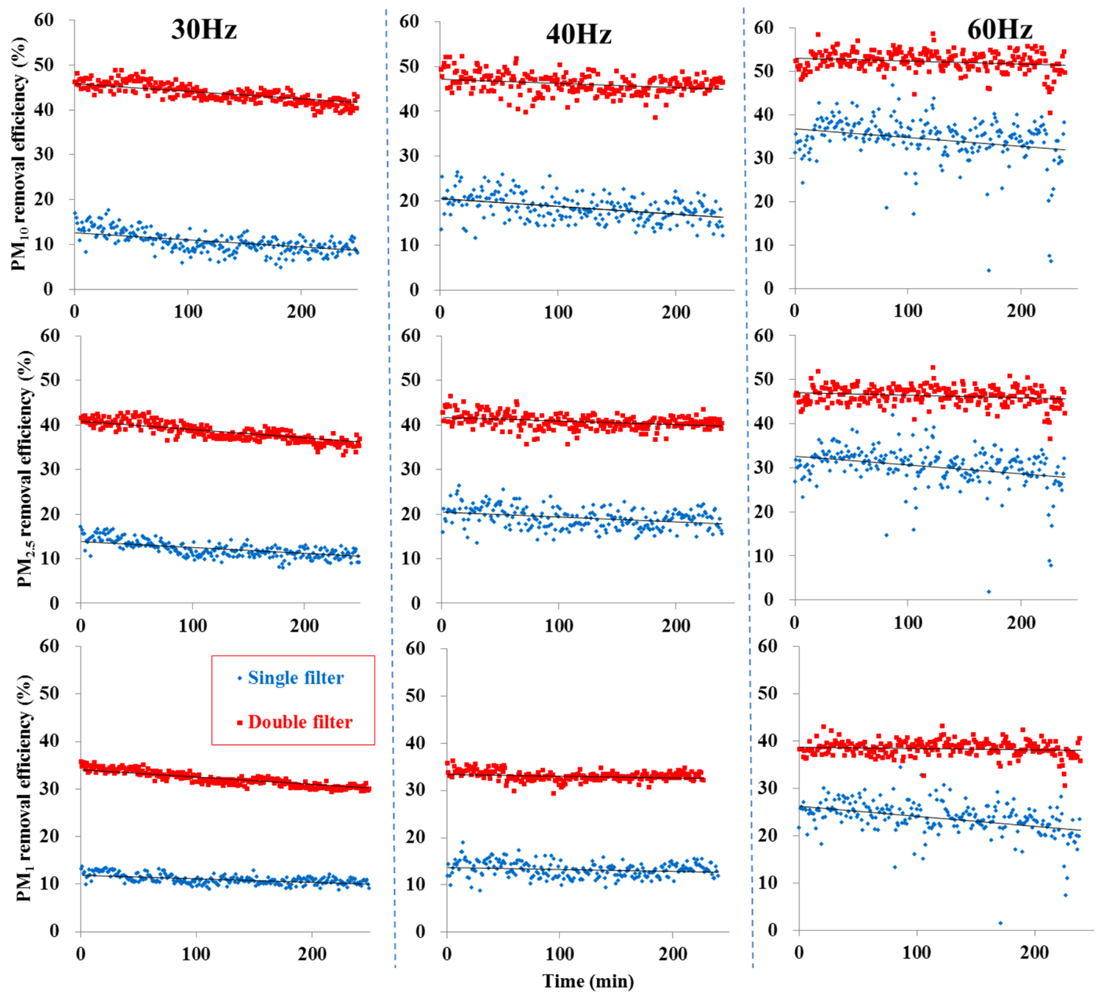

Figure 5. Variations on a PM removal efficiency by passage of time.

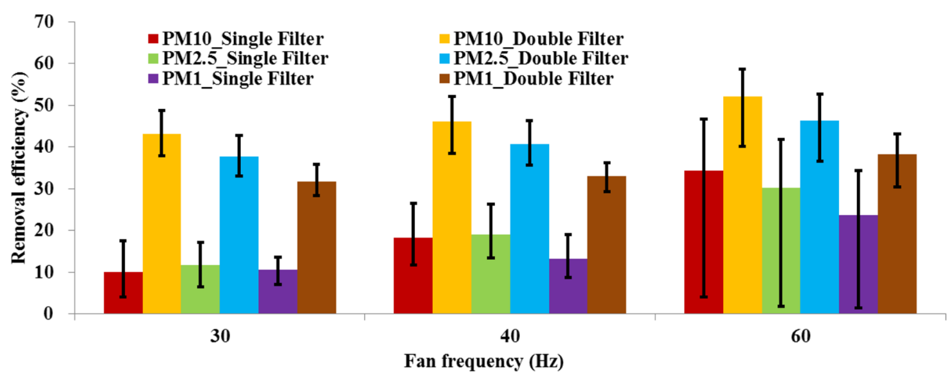

Figure 6. PM removal efficiencies with respect to different fan frequencies and number of filters (bar, mean; error bar, min − max).

or fan frequency increased. This result was similar with that of other studies on magnetic filters.[36−38] Removal efficiency depends on the magnetic force and drag force acting on the particle.[36] A magnetic filter will catch a particle when the magnetic force is higher than the drag force. Moreover, the magnetic force is proportional to the radius of a particle and the strength of the magnetic field; thus, the removal efficiency based on PM mass increases with increasing magnetic field intensity and particle size. In contrast, drag force depends proportionally on fluid viscosity. This means that the drag force decreases with decreasing viscosity. As a result, removal efficiencies also decrease with passage of time, indicating that PM removal efficiencies will decrease when dust-cake builds up on the magnetic filter surfaces. We calculated a linear regression equation for each fan operating condition. Generally, the slopes of the linear regression equation were negative values (from −0.0212 to −0.0029). This indicates that PM removal efficiency using a magnetic filter decreases with the passage of time as mentioned above.

Furthermore, not much difference was observed between the concentrations of $PM_{2.5}$ and PM_{10} in Table 1. When fan frequency was 60 Hz, removal efficiencies of PM_{10} were quite

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similar with those of $PM_{2.5}$. The differences in removal efficiencies between single filter and double filters were also lower than those of other frequencies. The reason was differences in wind velocity. At a high wind velocity, particle velocity is high and the particle concentration inside the tunnel does not change much at the same time. Therefore, as a rule of the material balance, the number of particles removed during a time period increases and the particle number per unit area decreases. Thus, fluid viscosity decreases. As mentioned above, drag force decreases because of decreasing viscosity. This means that removal efficiency will increase with increasing wind velocity.

A comparison of removal efficiencies between single and double filters by change of the fan frequency was conducted and is shown in Figure 6. In all cases, removal efficiency by the double filter was higher than that by a single filter. However, the difference in removal efficiencies between the single and double filters decreased as fan frequency increased.

Hence, higher removal efficiencies were observed with a stronger magnet field. The best removal efficiencies were observed with a fan frequency of 60 Hz and the double layer magnet filter installed. At 60 Hz of fan frequency using double filters, the maximum removal efficiency of PM_{10} and $PM_{2.5}$ was 58% and that of $PM_{1.0}$ was 43%. Furthermore, the stability of PM removal by the double filter (relative standard deviation (RSD), 3.2−5.8%) was higher than that by the single filter (10.9−24.5%) at all fan operating conditions.

In conclusion, PM removal efficiencies are related with wind velocity and magnetic field density. As fan frequency was increased and the number of filters was increased, removal efficiencies also increased. Throughout this study, the highest PM_{10} and $PM_{2.5}$ removal efficiencies were 58% and 45%, respectively, at 60 Hz with a double filter. Although this study was tested on single and double filters, the PM removal efficiency would be increased further if triple or more filters were used. Moreover, we used permanent magnets in this study, as they saved energy for ventilation. However, cleaning the filter was difficult and the magnetic field density was limited. Thus, electromagnets should be used in the field, as magnet field density can be easily controlled and cleaning is simple.

We only determined removal efficiencies based on the number of magnet filter layers and fan operating conditions. Additional research should be conducted regarding the life cycle of the magnet and other environmental effects on the magnet filter.

■ ASSOCIATED CONTENT

Supporting Information

Additional information for the linear regression equations and r^2 of calibration among three portable aerosol spectrometers. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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