Developing an Optimal Antiviral Method for the Air-filtration System of Subway Stations

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ABSTRACT

A novel antiviral method was developed in this study for the air-filtration system of subway stations. Using a dry aerosol coating process, along with a spark discharger and carbon-brush-type ionizer, we developed a high-performance antiviral air filter. Herein, Ag nanoparticles were produced using a spark–discharge generation system with an ion-injection system and were employed as antiviral agents for coating onto a medium-grade air filter. Moreover, we tested the pressure drop in the filter as well as its filtration efficiency and antiviral ability against aerosolized bacteriophage MS2 virus particles as a surrogate of the severe acute respiratory syndrome coronavirus 2 during dust loading. Notably, the dust contamination caused an increase in the filtration efficiency and pressure drop, whereas the antiviral agents (herein, the Ag nanoparticles) did not have a significant effect in this regard. Based on this, we suggested a novel method to regenerate the antiviral effect of the antiviral air filter contaminated by the dust particles. Furthermore, a theoretical analysis of the antiviral ability and antiviral effect regeneration for the case of dust loading was performed using a mathematical model to evaluate the time-dependent antiviral effect of the filter. Our model can be applied to the antiviral air-filtration system of subway stations to prevent the pandemic spread and predict the life cycle of antiviral filters.

Keywords: Antiviral air filter, Bioaerosols, Air-filtration system, Indoor air quality, Subway station

1 INTRODUCTION

Coronavirus disease 2019 (COVID-19) is an infectious disease (Britton et al., 2020; Nie et al., 2020) whose pathogen is a novel coronavirus (severe acute respiratory syndrome coronavirus 2). It first emerged in China in 2019, continued to terrorize the world until September 2021 (as of 30 September, 2021, the cumulative number of confirmed cases worldwide: approximately 233 million; the number of deaths: approximately 4.77 million) (CSSE at JHU, 2021). South Korea is no exception to this disease. The number of confirmed cases in South Korea increased substantially in September 2021, with the highest number being 3,271 on 25 September, which coincided with the trend observed in Seoul (KDCA, 2021) (Fig. 1). This suggests that South Korea, including Seoul citizens, is not immune from the risk of contracting the virus.

In particular, public’s anxiety about taking the subway, which is used by an unspecified number of people, is growing. The densely populated Seoul subway is a large-scale indoor facility with an average number of passengers being approximately 5.42 million per day in 2020 and approximately 1.5 million in rush hours (data provided by the Seoul Metro). Thus, the subway is not safe from the risk of the infection, and it would be difficult to identify the source of any infection. The Seoul Metro has stated that the probability of the infection is very low as long as people are wearing masks because each station is naturally ventilated as the doors open and close and the platforms and waiting rooms at subway stations have their own air-filtration system to purify and ventilate the air. Despite the Seoul Metro’s assurance, the Centers for Disease Control & Prevention recently...
recognized airborne inhalation of coronavirus, including droplets and aerosols, as the primary mode of transmission (CDC, 2021; Wang et al., 2021), and there have been several international cases of the coronavirus being detected in the air at subway stations (Hadei et al., 2021; Moreno et al., 2021). Furthermore, research has shown that coronavirus is detected even in the vents of negative-pressure wards in hospitals, where the air-filtration systems operate more strictly (Ahn et al., 2022). Thus, the possibility of contracting coronavirus in subway stations cannot be ruled out entirely; much attention is required for indoor-air-quality control for subway stations.

For subway stations, the indoor air quality is managed using an air-filtration system with an air filter. To save energy, air from the outside and some air returned from indoors are mixed; the mixture is then introduced to the inside. As most air-filtration systems are focused on filtrating fine dust particles (Jung et al., 2008; Kim et al., 2010; Kwon et al., 2010), they are vulnerable to microbial contamination, including bioaerosols such as the coronavirus. Recently, the coronavirus was detected in the air filter of the air-filtration system used for public transportation (Hadei et al., 2021), and studies have shown that the coronavirus can maintain its viability and infectivity for a long time in the filter (Chin et al., 2020). Thus, indoor air containing the coronavirus can be introduced back into the subway station by the air-filtration system contaminated with the coronavirus, resulting in a prolonged circulation and causing widespread of the virus. Recently, much effort has been made to stop the spread of the coronavirus through the development and installation of large-capacity air cleaners with an antiviral function at subway stations (Park et al., 2019c). However, this method is only effective locally in the space where the air cleaner is located. Thus, the antiviral technology must be adopted in an air-filtration system that circulates air in the entire area inside a subway station. As a result, the technology that coats the surface of the air filter of an air-filtration system used to purify the indoor air with an antiviral material to filter bioaerosols such as coronavirus and that hinders the survival of coronavirus can be proposed as a way to effectively prevent the spread of the infection at subway stations.

Furthermore, the air filters of air-filtration systems at subway station easily come in contact with pollutants such as indoor/outdoor fine dust, resulting in clogged pores in the filters and in a dropping pressure. When the pressure drop in the filter due to dust increases to a certain extent, air cannot pass through the filter, which expedites the replacement of the filter, shortening the filter lifetime and bringing more difficulties in operating the air-filtration systems of subway stations (Xu et al., 2013). In addition to the pressure drop in antiviral filters due to dust, the antiviral performance of the filter rapidly declines as the antivirally treated surface of the filter can also be clogged with dust, affecting the filter lifetime (Joe et al., 2016). Thus, there is an increasing demand for a technology that accurately predicts the degradation level of the antiviral performance of an antiviral filter caused by fine-dust contamination and that improves its antiviral performance to maximize the filter lifetime.

In this study, we suggest a method, involving the use of dry aerosol, that can provide high-performance antiviral ability to the filters of air-filtration systems used at subway stations and can
regenerate the antiviral performance affected by fine-dust contamination. We also numerically modeled this method that can maximize the filter lifetime. Moreover, the degradation of the antiviral performance was evaluated in the presence of real bioaerosols (airborne virus) to verify the effectiveness of the study results. Ultimately, after simulating the conditions of real subway station platforms, we proposed an optimal antiviral solution that can be applied to air-filtration systems.

2 METHODS

2.1 Fabrication of High-performance Antiviral Filters for Air-filtration Systems by Using a Dry Aerosol Coating Process

In this study, the antiviral ability was imparted to the filters of air-filtration systems by coating their surfaces with Ag nanoparticles, which are typically known as an antiviral agent. A panel-type nonwoven filter medium (Hwang et al., 2010), which is widely used in air-filtration systems at subway stations in Seoul, was selected and used in the coating process. Table 1 presents the characteristics of the filter medium. Ag nanoparticles were generated as an aerosol form by using a rod-to-rod-type spark discharger. To increase the specific surface area of the Ag nanoparticles and improve the uniformity of the coating, a carbon-fiber ion generator was installed in front of the spark channel to inject a large number of unipolar ions. The dry coating process was employed for the aerosol process.

Fig. 2(a) shows the antiviral agent coating process using the dry aerosol process. Ag nanoparticles, which were generated using the spark discharge, were used as the antiviral agent. In the spark discharger, two rod-type Ag electrodes (AG-402651, Nilaco, Japan) with a diameter of 10 mm and length of 100 mm were separated by a distance of 300 µm. A pulse-width-modulated alternating-current power source (voltage, 3.5 kV; frequency, 4.0 kHz, BPI-2K, Best Power) was applied using a high-voltage generator with a built-in switching circuit. Once a constant current is supplied through the power source, a voltage rises between both ends of the electrode. When the voltage between the electrodes reaches the spark-discharge-inception voltage, electrical energy is

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>Glass fiber</td>
</tr>
<tr>
<td>Thickness (L)</td>
<td>0.045 ± 0.005 cm</td>
</tr>
<tr>
<td>Solidity ((\alpha))</td>
<td>0.009 ± 0.005</td>
</tr>
<tr>
<td>Fiber diameter ((d_f))</td>
<td>1.1 ± 0.35 µm</td>
</tr>
</tbody>
</table>

Fig. 2. Schematic of the (a) antiviral coating and (b) dust loading process for the air filter.
momentarily discharged between the electrodes owing to the breakdown of air insulation, thereby generating sparks. The carrier gas introduced to the spark discharger is ionized by the collision with electrons emitted by the discharge. The ionized carrier gas and the emitted electrons collide with the Ag electrodes and locally make the temperature of the electrode surface extremely high, vaporizing the electrode surface. The vaporized Ag gas escapes the discharge area along the flow and is cooled rapidly, forming Ag nanoaerosols through condensation and coagulation processes (Byeon et al., 2008). Here, when a large number of unipolar ions are injected into the spark area, the condensed aerosol is momentarily unipolar charged and coagulation is suppressed to the limit by electrical repulsion between aerosols, resulting in the formation of Ag nanoaerosols with approximately 2–3 nm in size (Park et al., 2020a). Ag nanoparticles with suppressed coagulation have a larger specific surface than the coagulated Ag nanoparticles and thus can be expected to exhibit high antiviral performance when coated on the filter.

To generate Ag nanoaerosols, clean air, which was passed through the clean air compressor consisting of an oil trap, a diffusion dryer, and a high-efficiency particulate air (HEPA) filter, was introduced into the spark discharger at a flow rate of 2 L min\(^{-1}\) using a mass flow meter (Model 4043, TSI Inc., USA) and flow-control valve. The fabricated Ag nanoaerosols were coated onto the filter (40 × 40 mm\(^2\)) installed in the one-pass duct. At the front and rear ends of the filter, a sampling port was installed and the filter’s coating efficiency (\(\eta_{\text{coat}}\)) and coating surface density (\(\rho_{\text{coat}}\)) were calculated using the following equations by employing a scanning mobility particle sizer (SMPS) consisting of a neutralizer (Soft X-ray charger 4530, HCT Co., Ltd., Korea), classifier controller (model 3080, TSI Inc., USA), differential mobility analyzer (model 3081, TSI Inc., USA), and condensation particle counter (CPC; model 3022A, TSI Inc., USA).

\[
\eta_{\text{coat}} = 1 - \frac{C_{\text{down}}}{C_{\text{up}}} \tag{1}
\]

\[
\rho_{\text{coat}} = \frac{\eta_{\text{coat}} C_{\text{up}} Q}{A_{\text{filter}}} t \tag{2}
\]

where \(C_{\text{up}}\) and \(C_{\text{down}}\) represent the concentrations of Ag nanoparticles at the front and rear ends of the filter, \(Q\) represents the flow rate, \(A_{\text{filter}}\) represents the total cross-sectional area, and \(t\) represents the coating time. The analysis using a field emission scanning electron microscope (FE-SEM, JSM-7610F-Plus, JEOL, Japan) was also conducted to evaluate if Ag nanoparticles were properly coated onto the filter. Furthermore, changes in the pressure drop, particle removal performance, and antiviral performance of the filter were evaluated after coating.

### 2.2 Simulation of Fine-dust Contamination in the Filter for Air-filtration Systems at Subway Stations

Fig. 2(b) presents the simulated process of fine-dust contamination in the fabricated antiviral filter for air-filtration systems at subway stations. The Arizona test dust A4, which was specified in the ISO 12103-1 standard, was used as a test dust particle and as a mimic of fine dust because it had similar characteristics to the fine dust generated at subway stations (Woo et al., 2018). A certain amount of Arizona test dust was put into a lab-made dust feeder consisting of a glass Erlenmeyer flask, bar magnet, and stirrer, and clean air was blown at 5 L min\(^{-1}\) to collect the test dust on the filter (40 × 40 mm\(^2\)) installed in the one-pass duct. The mass of the dust captured in the filter was measured by comparing the weight of the filter before and after capturing the dust by using an electronic microscale (AS 82/220, RADWAG Corp., Poland). The pressure drop (\(\Delta P\)) in the filter, which changes according to the dust capture, can be calculated using the following equation (Brown, 1993).

\[
\Delta P = \frac{4 \mu a L u_0 (1 + 1.996 Kn)}{0.25 d_f^2 \left[ -0.5 \ln \alpha - 0.75 + \alpha - \frac{\alpha^2}{4} + 1.996 Kn \left(-0.5 \ln \alpha - 0.25 + \frac{\alpha^2}{4} \right) \right]} \tag{3}
\]
where $L$ refers to the thickness of the filter, $\mu$ refers to the dynamic viscosity of air, $d_f$ refers to the diameter of the filter fibers, $Kn$ is the Knudsen number, and $u_0$ refers to the flow rate passing through the filter. $\alpha$ refers to the filter solidity and can be defined as follows, for it changes according to the captured dust.

$$\alpha = \alpha' + \alpha_{\text{dust}}$$  \hspace{1cm} (4)

where $\alpha'$ refers to the solidity of the filter before capturing the dust, and $\alpha_{\text{dust}}$ refers to the solidity of the filter, which increases due to the dust capture and is defined as follows.

$$\alpha_{\text{dust}} = \frac{\text{volume of loaded dust}}{\text{volume of the sample}} = \frac{P_{\text{dust}} A_{\text{filter}}}{\rho_p A_{\text{filter}} L}$$  \hspace{1cm} (5)

where $\rho_p$ refers to the effective dust particle density, which was set to 3.1 g cm$^{-3}$ considering the chemical composition of the Arizona test dust used in this study (Joe et al., 2016).

In this study, the filter lifetime was determined as the time taken for the pressure drop to become twice compared to the initial value under the test conditions of a test wind speed of 2.5 m s$^{-1}$, in accordance with the test standards for air-filtration systems at subway stations (Kim et al., 2010). Thus, the dust capture per area ($\rho_{\text{dust}}$) was set to four cases: 0 (before capturing the dust), 330 ± 54, 660 ± 85, and 1000 ± 93 $\mu$g cm$^{-2}$. When $\rho_{\text{dust}} = 1000 \pm 93 \mu$g cm$^{-2}$, the pressure drop doubled compared to that of the filter before dust collection. Furthermore, changes in the pressure drop, virus capture performance, and antiviral performance of the filter were evaluated after capturing the dust.

### 2.3 Regeneration of the Antiviral Performance Using the Aerosol Process

In several previous studies, when antiviral performance was imparted to a fiber-type filter by coating nanometer-sized antiviral particles, the change in pressure drop due to the coating material was not significant (Joe et al., 2014, 2016; Gautam et al., 2019; Park et al., 2019a, 2019b, 2020a; Park et al., 2021). This implies that fine-dust contamination is the main cause of the change in the pressure drop. In addition, in case of antiviral filters, fine-dust contamination relatively creates more damage to the antiviral performance than causing increase in the pressure drop (Joe et al., 2016). More specifically, the lifetime of the filter is practically over because its function as an antiviral filter is lost because the antiviral performance degrades faster than the pressure drop in the filter is doubled from the initial value by fine-dust contamination.

In this study, when the antiviral filter loaded to the air-filtration system of subway stations underwent a decrease its antiviral performance below a certain level due to fine-dust contamination, the antiviral performance was regenerated by recoating the antiviral material using an aerosol process. Fig. 3 shows the schematic diagram of the antiviral-performance-regeneration experiment. When the antiviral performance decreased below 50% due to fine-dust contamination through the process described in Fig. 2(b), the Ag nanoparticles were recoated through the process.

![Fig. 3. Concept of the antiviral ability regeneration of the filter.](image-url)
described in Fig. 2(a) and the changes in the pressure drop, virus capture performance, and antiviral performance of the filter were evaluated after recoating.

2.4 Performance Evaluation of the Fabricated Antiviral Filter (Virus Capture and Antiviral Performance, Pressure Drop, and Coating-material-detachment Rate)

The virus capture and antiviral performance (Fig. 4(a)), pressure drop (Fig. 4(b)), and coating-material-detachment rate (Fig. 4(c)) of the fabricated antiviral filter were evaluated.

For the evaluation of the airborne virus capture and antiviral performance, bacteriophage MS2 virus (ATCC 15597-B1) (Joe et al., 2014, 2016; Park et al., 2019a, 2020b; Kang et al., 2021), an ribonucleic acid (RNA) virus such as coronavirus, which is often used as a mimic of infectious viruses, was aerosolized as a test virus particle by using an atomizer (Model 9302, TSI Inc., USA) (Fig. 4(a)). The flow rate in the duct between tests was controlled at 0.05 m s⁻¹, considering the operating conditions of the atomizer. To measure the virus capture efficiency, the test virus particles were introduced into the test duct and the particle-number concentration by particle diameter was measured at the front and rear ends of the filter sample using SMPS. The capture efficiency ($\eta_{\text{filt}}$) was calculated using the following equation.

\[
\eta_{\text{filt}} = 1 - \frac{N_{\text{down}}}{N_{\text{up}}}
\]

where $N_{\text{up}}$ and $N_{\text{down}}$ refer to the particle-number concentration of the virus particles at the front and rear ends of the filter, respectively.

The filter’s antiviral performance was evaluated using a plaque assay. Viral particles were captured on each filter sample (uncoated and fabricated filters) for 15 min using an atomizer, and then the virus on the filter was eluted into a solution phase using a urea-arginine phosphate buffer (U-APB) solution. After mixing a 0.1-mL virus-eluting U-APB solution with a 0.3-mL host-bacteria (E. coli strain C3000 (ATCC 15597)) solution and 29-mL tryptic-soy-agar solution, the mixture was smeared on a Petri dish and incubated for one day at 37°C. The number of plaques formed in the incubated Petri dishes was counted, and the antiviral efficiency ($\eta_{\text{anti}}$) was calculated using the following equation.

\[
\eta_{\text{anti}} = 1 - \frac{\text{PFU}_{\text{sample}}}{\text{PFU}_{\text{pristine}}}
\]

where \(\text{PFU}_{\text{pristine}}\) and \(\text{PFU}_{\text{sample}}\) refer to the number of plaque-forming units (PFU) eluted from the uncoated filter sample and the fabricated filter sample, respectively.

![Fig. 4. Schematic for the (a) bioaerosol-filtration-efficiency, (b) pressure-drop, and (c) detachment tests.](https://doi.org/10.4209/aaqr.230088)
To measure the pressure drop in the fabricated filter, clean air was introduced into the test duct where the filter sample was installed and the test wind speed was controlled at 2.5 m s⁻¹, in accordance to the test standards for air-filtration systems at subway stations, and the pressure drop at the front and rear ends of the filter sample was measured using a digital manometer (Model 435-1, Testo, Germany) (Fig. 4(b)). In addition, to evaluate the detachment rate of the coating material, a CPC was mounted at the rear end of the filter and the number of detached particles was measured for 60 min (Fig. 4(c)).

3 RESULTS AND DISCUSSION

3.1 Fabrication of High-performance Antiviral Filters for Air-filtration Systems Using a Dry Aerosol Coating Process

Fig. 5(a) shows the size distribution of the Ag nanoparticles generated by injecting a large number of monopolar ions (ion concentration: ~10⁷ ions cm⁻³) into the spark region. Without injecting the ions, the minimum value of the particle diameter was approximately 25.94 nm, with a particle-number concentration of 6.11 × 10⁶ particles cm⁻³. When the ions were injected, the minimum value of the particle diameter was approximately 10.55 nm, with a particle-number concentration of 3.47 × 10⁶ particles cm⁻³. Similar to previous studies, it is believed that injecting a large number of monopolar ions into the spark region may have instantaneously charged the condensed aerosol to monopolarity, inhibiting coagulation by the electrical attractive forces between the aerosols, resulting in smaller Ag nanoparticles (Park et al., 2020a). Furthermore, the SEM imaging verified that when the same amount (ρcoat, 10¹⁰ particles cm⁻²) of aerosols were coated onto the filter, the particles with the larger specific surface area were more evenly distributed owing to the inhibition of coagulation in the filter coated by injecting the ions (Fig. 6(b)), which results in the higher antiviral performance and lower deviation of performance (Fig. 6(c)). Thus, herein, a high-performance antiviral filter was fabricated by applying a large number of monopolar ions to the front end of the spark discharger using the dry aerosol method. The particle-number concentration at the rear end of the filter was 3.34 × 10⁵ particles cm⁻³, resulting in a filter-coating efficiency of approximately 90.4%. Using this, filter samples with four types of the coating area density (0, 2.0 × 10⁹, 6.0 × 10⁹, and 1.0 × 10¹⁰ particles cm⁻²) were fabricated.

3.2 Simulation of Fine-dust Contamination in the Filter of Air-filtration Systems at Subway Stations and its Antiviral Performance Regeneration

Fig. 6(a) shows the change in the pressure drop in the filter with the coating area density and severity of fine-dust contamination (dust-capture amount). The test was conducted under test...
Fig. 6. (a) Pressure drops, (b) filtration efficiencies, and (c) antiviral efficiencies of Ag-coated filters with various coating particle densities and dust contaminations.

conditions with a test wind speed of 2.5 m s⁻¹ (in accordance with the test standards for air-filtration systems at subway stations). The experimental results showed a trend similar to that of the change in the pressure drop in the filter due to dust capture, calculated using Eq. (3). In addition, the change in pressure drop due to the coating area density was minimal, but that due to severity of the fine-dust contamination was clearly demonstrated. This is also verified by the results of virus capture performance. Fig. 6(b) shows the performance of the fabricated filter for capturing bacteriophage MS2, which is an airborne virus. The minimum particle size and particle-number concentration of the viral aerosol were 20.1 nm and $1.63 \times 10^6$ particles cm⁻³, respectively.
In a previous study, the change in the capture performance of the filter due to fine-dust contamination was described using the following equation (Brown et al., 1988).

\[ \eta_{\text{filt}} = 1 - P_0 \exp[-\beta P_{\text{dust}}] \]  

where \( P_0 \) refers to the penetrability of the filter before the dust is captured and \( \beta \) refers to the coefficient that represents the material or performance of the filter. In this study, when \( \beta \) is set to \( 1.75 \times 10^{-3} \text{ cm}^2 \text{ mg}^{-1} \), the equation and experimental result were highly correlated. In terms of the filter’s capture performance, the change with respect to the coating area density was minimal, whereas the change with respect to the severity of fine-dust contamination was clearly demonstrated. This is because the increase in the solidity of the filter caused by the fine-dust contamination was much larger than that caused by the coating of Ag nanoparticles (around 100,000 times larger). Thus, it can be said that fine-dust contamination disrupts the flow through the filter, which substantially increases the pressure drop and capture efficiency (Joe et al., 2016) and does not considerably change the filter performance (pressure drop and capture efficiency) because it does not significantly disrupt the flow through the Ag nanoparticle–coated filter. By adopting this idea, we devised a method to regenerate only the antiviral performance without changing the filter performance by recoating the filter whose antiviral performance was degraded due to fine-dust contamination.

Fig. 6(c) shows the results of antiviral performance for the fabricated filter against airborne viruses with respect to the coating area density and fine-dust contamination. The antiviral performance increased as the coating area density increased, and it showed a clear trend of increasing as the severity of the fine-dust contamination decreased. When the coating area density was \( 1.0 \times 10^{10} \text{ particles cm}^{-2} \) and the severity of fine-dust contamination was 0, the antiviral performance was approximately 90.2%. In addition, when the coating area density was \( 1.0 \times 10^{10} \text{ particles cm}^{-2} \) and the severity of fine-dust contamination was \( 330 \mu \text{g cm}^{-2} \), the antiviral performance was approximately 52.5%. Under the above conditions, we performed the antiviral-performance-regeneration experiment using the criterion of antiviral performance regeneration set in this study (50% of the antiviral performance of less), and recoated Ag nanoparticles. Fig. 7(a) shows the regenerated antiviral performance of the antiviral filter whose coating area density is \( 1.0 \times 10^{10} \text{ particles cm}^{-2} \) and whose fine-dust contamination severity is \( 330 \mu \text{g cm}^{-2} \) after it was recoated. This figure verifies that when recoating area density (\( \rho_{\text{recoat}} \)) was \( 3.0 \times 10^{9} \text{ particles cm}^{-2} \), the antiviral performance was regenerated up to 90%. In addition, it verifies that the pressure drop or virus capture efficiency was not significantly changed after recoating the Ag nanoparticles (Fig. 7(b)). The above results verified experimentally that the antiviral filter lifetime was over due to degradation of the antiviral performance, which occurred before the end of the filter lifetime owing to an increase in the pressure drop caused by fine-dust contamination. Additionally, it was confirmed that the antiviral performance could be regenerated without sacrificing other performances of the filter. Thus, we
propose a solution that minimizes the infection risk in subway stations in Seoul if the proposed method can be applied to the air-filtration systems.

3.3 Evaluation of the Detachment Rate for the Fabricated Filter

To evaluate the detachment rate of the coating material for all the fabricated filters (pristine filter, Ag-coated filter, dust-loading filter, and Ag-recoated filter), clean air was introduced into the test duct where the filter samples were mounted and the number of detached particles was measured for 60 min using a CPC mounted on the rear end of the filter under a test wind speed of 2.5 m s\(^{-1}\) (in accordance to the test standards of the air-filtration system of subway stations). Fig. 8 shows the number of detached particles within 1 h of measurement. At the beginning of the measurement, up to six particles were detached, but it is not believed from the coating material because the particles were from the pristine filter. As one or two particles were sometimes measured even in clean air, it is concluded that the filter coated using the proposed method does not detach the coating material when used in the air-filtration system of subway stations.

3.4 Proposal of the Optimal Solution for Air-filtration Systems at Subway Stations

Numerical modeling to optimize the antiviral filter lifetime was performed in conditions of the air-filtration systems at subway stations in Seoul. The antiviral performance \(\eta_{\text{anti}}(t)\) over time can be modeled as follows according to a previous study (Joe et al., 2016).

\[
\eta_{\text{anti}}(t) = 1 - \exp \left[ - \left( \frac{\kappa_0}{1 + \gamma \dot{M}_{\text{depo}} t} \right) \frac{N_{\text{coat}}}{N_{\text{depo}} t} \right] \tag{9}
\]

where \(\kappa_0\) refers to the constant that represents the sensitivity between the virus and antiviral filter and \(\gamma\) refers to the conversion factor \([\text{cm}^2 \mu\text{g}^{-1}]\). \(\dot{M}_{\text{depo}}\) [\(\mu\text{g cm}^{-2} \text{ min}\)] and \(N_{\text{depo}}\) [PFU cm\(^{-2}\) min] refer to the amounts of dust and bioaerosols deposited on the antiviral filter, respectively, and can be expressed as follows:

\[
\dot{N}_{\text{depo}} = \eta_{\text{filt}} \dot{N}_{\text{in}} \tag{10}
\]

\[
\dot{M}_{\text{depo}} = \eta_{\text{filt}} \dot{M}_{\text{in}} \tag{11}
\]

where \(\dot{M}_{\text{in}}\) (\(\mu\text{g cm}^{-2} \text{ min}\)) and \(\dot{N}_{\text{in}}\) (PFU cm\(^{-2}\) min) refer to the amounts of dust and bioaerosols entering the antiviral filter, respectively, and \(t\) refers to the operating time of the filter. Based on the above equations, the specifications of air-filtration systems in representative subway stations...
in Seoul were investigated to predict the lifetime of the antiviral filter applied to the air-filtration systems at subway stations over time, which are presented in Table 2 (Kim et al., 2010). For the inlet flow rate ($Q$) of the air-filtration system, an average value of 580 m$^3$ min$^{-1}$ was used and a capture efficiency ($\eta_{\text{filt}}$) of 80% was used. It is known that the cross-sectional area of the filters for air-filtration systems in subway stations is 10 m$^2$. We also used the results from a previous study (Jung et al., 2008), taking the concentration of dust entering an air-filtration system at a subway station as 100 µg m$^{-3}$. The concentration of bioaerosol was assumed to be 100 PFU m$^{-3}$, and we included a regeneration process when the antiviral performance drops below 50%. Fig. 9(a) shows the filter lifetime calculated using the increase in the pressure drop in Eq. (3) and that calculated using the antiviral performance degradation in Eq. (9). To validate the proposed numerical model, an additional experiment was conducted. Fig. 9(b) shows the plaque assay results on the fine-dust-contaminated antiviral filters at various times (P1–P4) in Fig. 9(a). It demonstrated that the antiviral filter lifetime could be effectively prolonged by regenerating antiviral of the filter ability.

<table>
<thead>
<tr>
<th>Station</th>
<th>Flow rate (m$^3$ min$^{-1}$)</th>
<th>Pressure drop (mmH$_2$O)</th>
<th>Filtration Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seoul</td>
<td>642</td>
<td>89</td>
<td>80</td>
</tr>
<tr>
<td>Myeongdong</td>
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<tr>
<td>Yeouido</td>
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<td>120</td>
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![Fig. 9. Regeneration modeling of filter lifetime and (b) plaque assay results with specific points (P1–P4).](image-url)
via recoating the filter with antiviral agents. By applying this method with minimal modifications to the existing air conditioning system, it is possible to propose an optimal solution for automatically performing anti-viral recoating when the filter’s pressure drop reaches the critical level (Fig. 10). Based on these findings, the regeneration of antiviral ability can be a potential solution to prevent coronavirus infection in subway stations by extending the lifetime of the antiviral filter.

4 CONCLUSIONS

Herein, we introduced a method to develop a high-performance antiviral filter using a dry aerosol process as an optimal antiviral method for air-filtration systems at subway stations. We also proposed a new method that can help regenerate the antiviral performance degraded by fine dust. We evaluated the proposed method to determine if it was effective by using airborne viruses that mimic the real coronavirus. The results verified that the degraded antiviral performance regenerates without damaging other properties of the filter. We also numerically modeled the situation of applying the proposed method to the filters of the air-filtration systems used in the Seoul subway stations. The proposed method is highly practical as it can be applied to the filters without further complications. As we proved its effectiveness against airborne viruses, the proposed method is an optimal antiviral solution that can be applied to air-filtration systems at subway stations. Based on this method, we hope to minimize the confirmed cases of the coronavirus in the Seoul subway, public transportation across the nation, and multicomplex facilities around the world, and we hope that our study will serve as a stepping stone to effectively prevent the spread of the another coronaviruses.
ACKNOWLEDGMENTS

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