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Application of corona discharge-generated air ions for filtration of aerosolized virus and inactivation of filtered virus

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ABSTRACT

The effect of corona discharge-generated air ions on the filtration of aerosolized bacteriophage MS2 was studied. A carbon-fiber ionizer was installed upstream of a medium-efficiency air filter to generate air ions, which were used to charge the virus aerosols and increase their filtration efficiency. After the virus aerosols were captured by the filter for a certain time interval, they were exposed to a newly incoming air ion flow. Captured virus particles were detached from the filter by sonication, and their antiviral efficiency due to air ions was calculated by counting the plaque-forming units. The antiviral efficiency increased with ion exposure time and ion concentration. When the concentration of positive air ions was 10^7 ions/cm^3, the antiviral efficiencies were 46.1, 78.8, and 83.7% with exposure times of 15, 30, and 45 min, respectively. When the ionizer was operated in a bipolar mode, the number concentrations of positive and negative ions were 6.6×10^6 and 3.4×10^6 ions/cm^3, respectively, and the antiviral efficiencies were 64.3, 89.1, and 97.4% with exposure times of 15, 30, and 45 min, respectively. As a quantitative parameter for the performance evaluation of air ions, the susceptibility constant of bacteriophage MS2 to positive, negative, bipolar air ions was calculated as 5.5×10^{-3}, 5.4×10^{-3} and 9.5×10^{-3}, respectively. These susceptibility constants showed bipolar ion treatment was more effective about 1.7 times than unipolar ion treatment.

1. Introduction

Particles of biological origin, such as viruses, bacteria, fungi, and pollen—as well as their fragments—that are present in air are referred to as bioaerosols. Bioaerosols can cause serious health hazards when they contaminate a human environment. The influenza virus, severe acute respiratory syndrome, and the avian and swine flu are natural examples illustrating the profound, everyday impacts of bioaerosols on public health (Jung, Lee, & Kimet, 2009). Virus particles are only nanometers in size, so they can remain suspended in the air long enough to be dispersed (Joe, Park, & Hwang, 2016). Filtration is one of the most common methods for removing airborne particulates. It has been applied in various situations, including personal facepiece respirators and central heating, ventilating, and air-conditioning (HVAC) systems of buildings because it can achieve a high removal efficiency of aerosol particles. Fibrous filters are simple and economical devices capable of efficiently removing submicrometer particles (Wang & Otani, 2013; Sim, Park, Bae, & Jung, 2015). Typical filters work using conventional mechanical mechanisms (i.e., impaction, interception, and diffusion). For improving the filtration efficiency and decreasing the pressure drop, electric fields are applied and/or charging particles are used.

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A charged particle polarizes the fiber and consequently experiences an image force that is equal to the Coulombic force between the charge on the particle and an equal, but opposite, charge placed inside the fiber at a position corresponding to the optical image of the particle (Wang, 2011). Ionizer-assisted fibrous filter media were designed to increase the removal efficiency without increasing the pressure drop. Lee, Yermakov, and Grinshpun (2004, 2005) used facepiece respirator filters, and showed that the continuous emission of unipolar air ions by corona-ionizing air purifiers in the vicinity of a disposable half-mask respirator enhanced its protection characteristics against fine and ultrafine particles. Huang, Agranovski, Pyankov, and Grinshpun (2008) examined the effect of ion-induced enhancement on the filtration of an HVAC filter with biological aerosols, including aerosolized bacterial cells and viruses. Park, Yoon, and Hwang (2011) and Noh, Lee, Kim, Yi, Hwang, and Yoon (2011) tested the increase in particle filtration with a pair of carbon-fiber ionizers installed upstream of a glass fiber air filter and an electret filter, respectively.

An externally applied electric field polarizes the fiber, acting as a linear dipole and creating a nonuniform field around the fiber. A charged particle in such a nonuniform electric field experiences a force, in addition to the force exerted by the externally applied field (Wang, 2011). Lee, Kim, Shin, Lee, Ku, and Shin (2011) evaluated the performance of a two-stage electrostatically augmented air filter consisting of a positive corona precharger located upstream of the filter and an electrified filter collector coupled with an external electrical field. Kim, Sioutas, and Chang (2000) utilized a stainless-steel fibrous filter as the ground electrode of a point-to-plate electrostatic precipitator so that the particle-laden flow passed through the filter. Inculet et al. (2002) used pseudoelectret fibers consisting of two very-fine-diameter wires that were assembled closely together but electrically isolated from each other with a Teflon coating. When a voltage was applied to the wires, a local high-intensity electric field was produced between the two wires, and charged particles were attracted by the assembly.

Although airborne particles can be removed by filters, indoor bioaerosols accumulate in large quantities on the filters, where they can multiply under certain conditions, especially if high amounts of moisture are present on the filters. Moreover, the organic or inorganic materials deposited on the filter media after air filtration contribute to microbial growth (Verdenelli, Cecchini, Orpianesi, Dadea, & Cresci, 2003). This inevitably leads to a decreased filter efficiency and, probably, to the deterioration of the filters and the eventual release of microorganisms.

There are various controlling technologies for inactivating aerosolized microorganisms, including air ionizers, heaters and dryers, chemical treatment, photocatalytic oxidation, ultraviolet germicidal irradiation (UVGI), and dielectric barrier discharge. Carbon-fiber ionizers produce stable unipolar ions in sufficiently high concentrations with little ozone generation and secondary particles (Han, Kim, Kim, & Sioutas, 2008; Park, Yoon, Kim, Byeon, & Hwang, 2009; Kim, Yoon, Park, & Hwang, 2011; Noh et al., 2011; Park et al., 2011). Thus, they have been considered for use in indoor air purifiers to generate air ions. Park et al. (2009) installed carbon-fiber ionizers in front of a fibrous medium filter to study the effect of air ions on the inactivation of *Escherichia coli*. Kim et al. (2009) also used carbon-fiber ionizers and studied the antibacterial effects of air ions with different ion exposure times, ion concentrations, polarities of generated ions, and different kinds of bacteria. Lee, Hyun, and Hwang (2014) inactivated aerosolized *Staphylococcus epidermidis* using both positive and negative air ions simultaneously to achieve a higher inactivation efficiency. Many researchers have studied ionizers for inactivation of bioaerosols; however, the elimination of airborne viruses has not been considered. Huang et al. (2008) performed a removal test of the influenza virus A strain (H11N9) with unipolar air ions. They reported the removal efficiency achieved not by inactivation but by filtration.

Because different experimental conditions (such as the flow rate, residence time, and power consumption) have been used in previous studies on ionizers, direct comparison of the inactivation efficiencies of different ionizers is difficult. Moreover, for industrial applications, quantitative parameters are needed for design optimization, performance evaluation, and the prediction of the power consumption of ionizer systems. As one quantitative parameter, the susceptibility has been applied in numerical models to evaluate the antimicrobial effects of an upper-room UVGI system against bioaerosols and the antimicrobial activities of silver and copper nanoparticles or air ions against test bacteria (Beggs, Noakes, Sleigh, Fletcher, & Kerr, 2006; Yoon, Byeon, Park, & Hwang, 2007; Kim et al., 2011).

In this study, test viruses were aerosolized and captured on a fibrous filter. A carbon-fiber ionizer was installed to generate air ions and charge aerosolized viruses so that the charged virus aerosols could be captured on the filter. A stainless-steel mesh was installed near the filter to apply an additional external electric field to the charged virus aerosols so that the filtration efficiency could be increased. Viruses deposited on the filter were then exposed to a newly incoming air ion flow as well as an electric field. The effects of the ion concentration, ion polarity, and ion exposure time on the antiviral efficiency were examined. As a quantitative parameter for the performance evaluation of air ions, a susceptibility constant of the airborne virus to air ions was introduced for the first time, to our knowledge.

2. Experimental

2.1. Preparation of virus solution

The bacteriophage MS2 virus (ATCC 15597-B1) and Escherichia coli strain C3000 (ATTCC 15597) were selected as the test virus and host bacteria, respectively. To recover the bacterial cells from the freeze-dried state, 10 mL of tryptic soy broth (TSB) was mixed with the freeze-dried bacterial cells, and the mixture was subjected to shaking incubation for 24 h at 37 °C. 0.1 mL of the incubated bacterial solution was injected into the 10 mL of TSB. Then, the bacterial solution-injected TSB solution was used as a host bacterial solution after further shaking incubation for 6 h at 37 °C.

Next, 1 mL of TSB was injected into the freeze-dried MS2 virus, and 0.1 mL of the virus with the TSB solution was extracted. The extracted solution was mixed with 0.3 mL of the host bacterial solution and 29 mL of soft tryptic soy agar (TSA) containing 8 g/L of

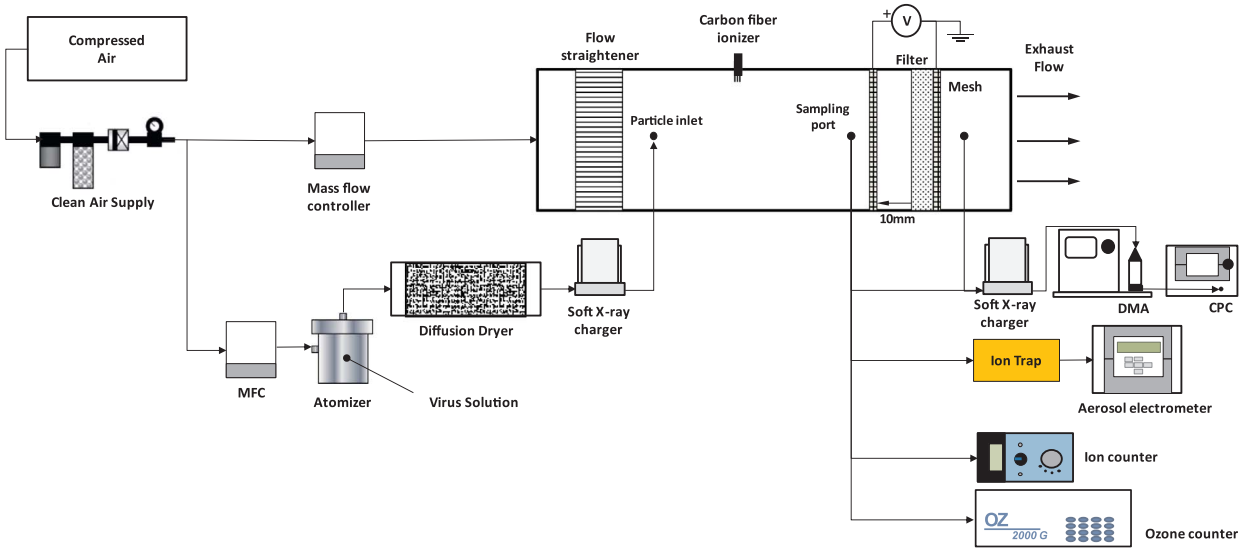

Fig. 1. Experimental setup.

agar. The produced agar solution was poured onto a Petri dish and then incubated overnight at 37 °C. The surface of the agar was scraped off with 10 mL of a phosphate buffer solution whose pH was maintained as 7.0. The solution was centrifuged for 20 min at 5000 × g, and the supernatant was conserved. The supernatant was used as a virus solution.

2.2. Filtration of aerosolized MS2

Experiments were performed with the experimental setup shown in Fig. 1. The system consisted of a test duct, a particle-generation system, and a measurement system. The test duct, with a cross-sectional area of $0.04 \times 0.04\ m^2$ and a length of 1 m, was made of acryl. A glass fiber filter was installed in the middle of the test duct. The thickness of the filter was 0.3 mm, as measured by an optical microscope. The average fiber diameter was 6.0 μm, as determined using scanning electron microscope (see Fig. 2). The solidity was determined to be 0.27 using the following equation (Davies, 1973) with the pressure drop measured with a pressure gauge (Magnehelic 2000, Dwyer Instruments Inc., USA):

$$\Delta p = \frac{64\mu L u_0 \alpha^{1.5}(1 + 56\alpha^3)}{{d_f}^2} \tag{1}$$

where μ is the viscosity of air, L is the filter thickness, u_O is the face velocity at the filter media ($=u/(1-\alpha)$, where u is the flow velocity), α is the filter solidity, and d_f is the fiber diameter. The flow velocity was changed from 0.1 to 1.0 m/s. Isokinetic sampling

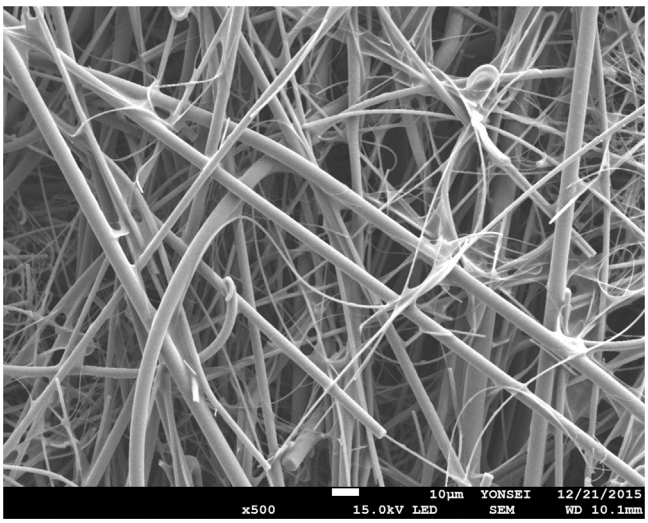

Fig. 2. Scanning electron microscope image of glass fiber filter.

probes were located at the front and back of the filter media for aerosol sampling. Two woven-wire stainless-steel mesh screens were installed immediately behind the filter and 10 mm ahead of the filter to apply an electric field across the filter. The thickness of the mesh screen and the opening area fraction were 0.3 mm and 69.9%, respectively.

Compressed air was used as a carrier gas after oil droplets, moisture, and contamination particles were removed by a clean-air supply system, which consisted of an oil trap, a diffusion dryer, and high-efficiency particulate air filter. To aerosolize the virus particles, 0.1 mL of the virus solution was diluted with 50 mL of deionized water. The diluted virus solution was aerosolized with a Collison-type atomizer (9302, TSI Inc., USA). Dry clean air of 2 L/min formed a high-velocity jet through an orifice in the atomizer. The pressure drop caused by this jet drew the virus solution up through a tube. The solution was then broken into droplets by the high-velocity air jet. The resultant larger droplets impinged on an impactor, while the smaller droplets made no contact and formed an aerosol that exited through an outlet. The aerosolized viruses passed through a diffusion dryer for water removal and a neutralizer (Soft X-ray Charger 4530, HCT, Korea) to induce a Boltzmann charge distribution. Another portion of clean air was delivered to the test duct and mixed with the particle-laden air flow. The mixture flow rate was varied among 28.8, 48.0, and 96.0 L/min in order to achieve flow velocities of 0.3, 0.5, and 1.0 m/s, respectively.

A carbon-fiber ionizer was positioned at the top of the test duct, 20 cm ahead of the filter media. It consisted of an ion emission tip and a power pack. The ion emission tip consisted of a 300 ± 50 carbon-fiber bundle, and the diameter of each carbon fiber was approximately 5–10 μm. The number concentration of air ions generated from the carbon-fiber ionizer depended on the output voltage and the frequency of the ionizer. Positive air ions were generated for the filtration test. For this, the output voltage of the ionizer was a 1–3 kV (peak-to-peak: 60 Hz) sawtooth waveform with an operation current less than a few μA.

The concentration of the test particles was measured using a scanning mobility particle sizer (SMPS) system consisting of a classifier controller (3080, TSI Inc., USA), a differential mobility analyzer (DMA, 3085, TSI Inc., USA), a condensation particle counter (CPC, 3775, TSI Inc., USA), and a neutralizer (Soft X-ray Charger 4530, HCT, Korea) with a sampling air flow rate of 0.3 L/min. The fractional particle filtration efficiency, $\eta_{filtration}(d_p)$, was experimentally obtained using the following equation:

$$\eta_{filtration}(d_p) = 1 - \frac{C_{downstream}(d_p)}{C_{upstream}(d_p)}, \tag{2}$$

where $C(d_p)$ is the number concentration of the aerosolized MS2 bacteriophage virus with size d_p obtained from the SMPS measurements.

The fractional particle-filtration efficiency was obtained using the following equation:

$$\eta_{filtration}(d_p) = 1 - \exp\left(-\frac{4\alpha L E_{\Sigma}(d_p)}{\pi d_f(1-\alpha)}\right). \tag{3}$$

The single-fiber (fractional) filtration efficiency, $E_{\Sigma}(d_p)$, was defined as

$$E_{\Sigma}(d_p) = 1 - \{1 - E_{diff}(d_p)\}\{1 - E_{\mathrm{int}}(d_p)\}\{1 - E_{imp}(d_p)\}\{1 - E_{img}(d_p)\}\{1 - E_{field}(d_p)\}, \tag{4}$$

where $E_{diff}(d_p)$, $E_{int}(d_p)$, and $E_{imp}(d_p)$ represent the filtration efficiencies due to Brownian diffusion, interception, and inertial impaction, respectively.

The single-fiber filtration efficiency by an image force, $E_{img}(d_p)$, was given as

$$E_{img}(d_p) = \frac{2}{h_k^{1/2}}\left[\left(\frac{D_f - 1}{D_f + 1}\right)\frac{\{n(d_p)e\}^2}{12\pi^2\mu u_0 \varepsilon_0 d_p d_f^2}\right]^{\frac{1}{2}}, \tag{5}$$

where D_f is the dielectric constant of filter fiber, ε_O is the permittivity of air, $n(d_p)$ is the charge number of particles with size d_p, e is the elementary unit charge, and h_k is the Kuwabara hydrodynamic factor. The single-fiber filtration efficiency by an external electric field, $E_{field}(d_p)$, is given as

$$E_{field}(d_p) = \frac{N_{field}}{N_{field} + 1}\left[\left(\frac{D_f - 1}{D_f + 1}\right) + 1\right], \tag{6}$$

$$N_{field} = \frac{En(d_p)e}{3\pi\mu d_p u_0}, \tag{7}$$

where E is the strength of the applied electric field. For details about these efficiencies, readers are referred to Brown (1993) and Hinds (1999).

Using the fractional particle-filtration efficiency, the overall filtration efficiency, $\eta_{filtration}$, was obtained as

$$\eta_{filtration} = 1 - \frac{\sum \eta_{filtration}(d_p) C_{upstream}(d_p)}{\sum C_{upstream}(d_p)}. \tag{8}$$

The average charge number per particle was determined by electrical-current measurements using an aerosol electrometer (3068B, TSI, USA), and the air was sampled at an air flow rate of 0.3 L/min using a vacuum pump. The sampled air flow passed through an ion trap, where an average electric field of 200 V/cm was applied to eliminate gaseous ions. The average charge number

per particle, n, was then calculated using the following equation

$$n = \frac{I}{eQ\sum C_{upstream}(d_p)}, \tag{9}$$

where I is the current, and Q is the sampling flow rate.

Theoretically, the average charge number per particle was determined as follows:

$$n = \frac{\sum n(d_p)C_{upstream}(d_p)}{\sum C_{upstream}(d_p)}, \tag{10}$$

The following classical diffusion charging equation was used;

$$n(d_p) = \frac{d_p kT}{2K_E e^2}\ln\left[1 + \frac{\pi K_E d_p v_{ion} e^2 C_{ion}\tau}{2kT}\right], \tag{11}$$

where K_E is the electrostatic constant of proportionality (9×10^9 N·m^2/C^2). The mean thermal speed of an air ion, v_{ion}, is 235 m/s, as defined by Hinds (1999), and τ is the charging time. The following Birth and Death equation was also used (Boisdron & Brock, 1970):

$$\frac{dC_{upstream,j}(d_p)}{dt} = \beta_{j-1}C_{upstream,j-1}(d_p)C_{ion} - \beta_j C_{upstream,j}(d_p)C_{ion}, \tag{12}$$

where $C_{upstream,j}$ is the number concentration of particles with j elementary charges, C_{ion} is the ion number concentration, and β_j is the combination coefficient of ions with particles carrying j elementary charges. The equation for combination coefficient β_j is shown in Fuchs (1963). Then the charge number of particles with size d_p, $n(d_p)$, was calculated using the following equation.

$$n(d_p) = \frac{\sum_j j\cdot C_{upstream,j}(d_p)}{\sum_j C_{upstream,j}(d_p)} \tag{13}$$

The ion concentration and ozone concentration were measured using an air ion counter (Air Ion Counter, AlphaLab, Inc., USA) and an O_3 monitor (OZ 2000 g, Seres, France), respectively. The temperature and relative humidity inside the test duct were 22.5 ± 3 °C and 10 ± 5%, respectively.

2.3. Inactivation of captured MS2

The bacteriophage MS2 was aerosolized using the atomizer at 2 L/min and captured on a filter for 30 min. The virus-captured filter was exposed to air ions carried by 5 L/min of clean air. The exposure time was varied between 15 and 45 min. Unipolar air ions were generated by varying the concentration from 1.0×10^6 to 1.0×10^7 #/cm^3. The output voltage of the ionizer used for the unipolar mode was 1–3 kV (peak-to-peak, 60 Hz), sawtooth wave form. Positive air ions and negative air ions were generated separately. Then bipolar air ions having positive and negative ion simultaneously were generated to study the ion polarity effect on inactivation. For the bipolar mode, the output voltage was changed to a sine wave to a 16 kV peak-to-peak voltage, so the bipolar ion concentration was also varied from 1.0×10^6 to 1.0×10^7 #/cm^3. The ratio of positive ions to negative ions was 2:1. The difference between the electrical mobilities of the positive ion (~1.1 cm^2/V·s) and negative ion (~1.9 cm^2/V·s) caused the positive-ion concentration to be higher than the negative-ion concentration (Noh et al., 2011).

After the exposure test, each test filter was placed in 10 mL of deionized water and subjected to sonication for 10 min via a batch-type sonicator (KMC1300V, Vision scientific, Korea) to detach the deposited virus particles from the filter. Then, 0.1 mL of the water containing the virus particles was mixed with 0.3 mL of a host bacterial solution and 29 mL of soft TSA. After the mixed solution was poured on a Petri dish and incubated overnight at 37 °C, plaques were formed. The number of plaques was counted, and the antiviral efficiency of the air ions was defined by the following equation:

$$\eta_{antiviral} = 1 - \frac{\mathrm{PFU}_{\mathrm{exposedtoion}}}{\mathrm{PFU}_{\mathrm{exposedtocleanair}}}, \tag{14}$$

where the numerator is the number of plaque-forming units (PFU) on the nutrient agar plate after incubation when the filter was exposed to air ions, and the denominator is the number of PFUs on the nutrient agar plate after incubation when the filter was exposed to clean air. In addition to the exposure test with air ions, an exposure test with an external electric field was performed.

Susceptibility has been used to explain the relative importance of various parameters affecting antimicrobial efficiency, such as the number concentration of generated ions, applied electric-field strength, and exposure time. Yoon et al. (2007) applied a susceptibility constant to evaluate the antibacterial effects of silver and copper nanoparticles. Kim et al. (2011) applied a susceptibility constant to evaluate the antibacterial effects of corona discharge-generated air ions. In this paper, the susceptibility constant Z of the MS2 virus to air ions is defined as

$$Z = \frac{-\ln(1-\eta_{\mathrm{antiviral}})}{\mathrm{N_{ion}}}, \tag{15}$$

where N_{ion} is the number of air ions reaching single virus particle captured on a filter (ions/particle) and expressed as follows:

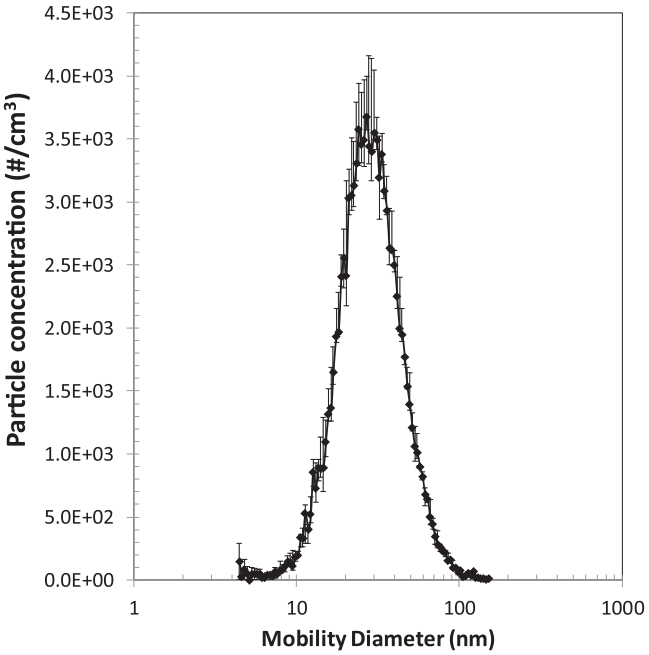

Fig. 3. Size distribution of aerosolized bacteriophage MS2.

$$N_{ion} = \frac{\text{(ions reached to filter)}}{\text{(virus captured on filter)}} = \frac{C_{ion} \times t_{exposure} \times Q_{exposrue}}{\eta_{filtration} \times C_{upstream} \times t_{capture} \times Q_{capture}}. \quad (16)$$

where $t_{exposure}$ is the ion exposure time and $t_{capture}$ is virus capturing time. $Q_{exposure}$ is the flow rate when the virus was exposed to the air ions and $Q_{capture}$ is the flow rate when the virus was captured on the filter.

3. Results and discussion

3.1. Particle charging test

Aerosolized bacteriophage MS2 particles entered the test duct and passed through the stream of air ions. Fig. 3 shows the particle size distribution. The total number concentration and the geometric mean diameter were 1.06×10^5 #/cm^3 and 27.6 nm, respectively. The positive unipolar air ions were generated from the carbon-fiber ionizer, and their concentration was maintained as 1.5×10^7 #/cm^3 with different flow velocities. When the polarity of the ionizer was changed so that negative unipolar ions were generated, the ion concentration was adjusted to be the same as that for positive ions. The virus aerosols were charged, and the average particle charge numbers were determined using Eq. (9). The results are summarized in Fig. 4. The average charge numbers were also obtained by the classical diffusion charging theory using Eqs. (10) and (11): 0.89, 0.72, 0.51 at flow velocities of 0.3, 0.5, 1.0 m/s, respectively. In addition, the charge numbers were obtained by the Birth and Death equation using Eqs. (10) and (13), and found to be 0.85, 0.67, 0.41 at flow velocities of 0.3, 0.5, 1.0 m/s, respectively. There were not much differences in using two different theories. These theoretical results agreed with the experimental results (Eq. (9)) of 0.93, 0.76, 0.47 at flow velocities of 0.3, 0.5, 1.0 m/s, respectively.

3.2. Filtration test

Table 1 shows overall filtration efficiencies (experimental) determined using Eqs. (2) and (8). When both the ionizer and the external electric field were turned off, the filtration efficiencies were 56.5, 48.9, and 31.9% for flow velocities of 0.3, 0.5, and 1.0 m/s, respectively. When the ionizer was turned on, the virus particles were charged by air ions, and the filtration efficiency increased, e.g., to 63.5% for a flow velocity of 0.3 m/s. The application of an external electric field of 2 kV/cm further increased the filtration efficiency to 71.7%. For a higher flow velocity, the efficiency increased owing to the ionizer, and the electric-field strength decreased slightly. Table 1 also shows the theoretically calculated overall filtration efficiencies, which were obtained using Eqs. (3) and (8). The results show that the theories used in this study slightly underestimated the efficiency. Table 1 shows that the pressure drops were 13.3, 22.5, and 46.0 mm H_2O for flow velocities of 0.3, 0.5, 1.0 m/s, respectively, regardless of whether the ionizers and stainless-steel mesh screens were installed.

Fig. 5 shows the effects of the air ions and electric field on the fractional filtration efficiencies (experimental) for a flow velocity of 0.3 m/s. The ion concentration was 1.5×10^7 ions/cm^3, and the electric-field strength was 2 kV/cm. For particles larger than 15 nm,

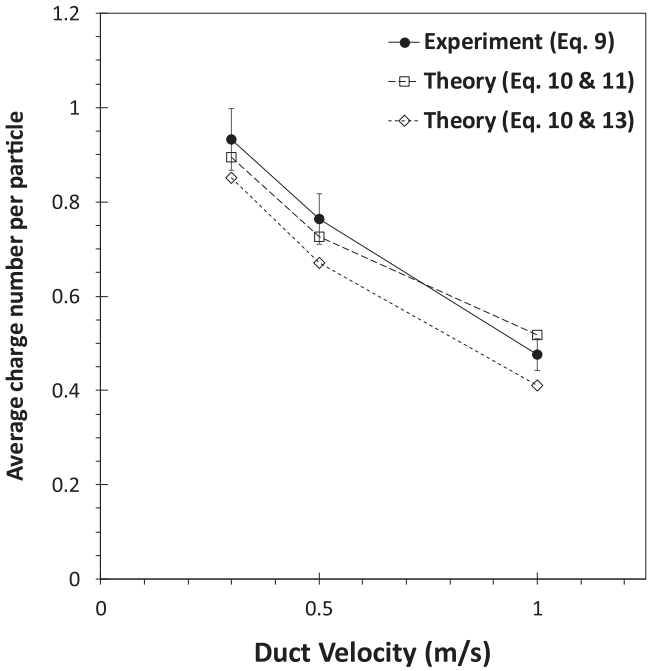

Fig. 4. Average charge number per particle with variation of duct velocity.

the increments in the efficiency due to the air ions and electric field were clearly observed. However, for particles smaller than 15 nm, the increments of the efficiency were indistinguishable, as very small particles have low charge numbers and are thus difficult to be measured. Data analysis was performed for Fig. 5 using paired t-test with SPSS Statistics Version 23. There was a significant average difference between filtration efficiencies ($t_{filter\text{-}ionizer} = 10.292$, $t_{filter\text{-}field} = 17.813$, $p < 0.05$ for both).

3.3. Antiviral test

Virus particles might lose their viability after they were captured on the filter and exposed to dry air. Experiments were carried out for investigating natural viability decay without using air ionizer. The average PFU numbers were 135, 124, 138, 130 when the captured virus particles were exposed clean dry air for 0, 15, 30, 45 minutes, respectively. The results imply that the dry air did not affect the viability of virus during our experiments.

The antiviral efficacy with air ions was studied for various ion exposure times and ion concentrations. The effect of ion polarity on the antiviral efficacy was also studied. The results are plotted in Fig. 6. Data analysis was performed using paired t-test with SPSS Statistics Version 23. Fig. 6 shows that the antiviral efficiency increased as the exposure time or the amount of air ions increased. The antiviral efficiencies of positive air ions with 10^7 ions/cm^3 concentration were 46.1, 78.8, and 83.7% for exposure times of 15, 30, and 45 min, respectively, while the efficiencies of negative air ions with the same concentration were 48.1, 77.6, and 82.3%. Therefore, the ion polarity did not affect the efficiency, for unipolar air ions ($p > 0.05$). Kim et al. (2011) studied the effect of air ions on the inactivation of bacteria (*Escherichia coli* and *Staphylococcus epidermidis*) captured on a membrane filter. In their study, the antibacterial efficiency also increased when the ion concentration and exposure time increased.

Fig. 6 also shows that the antiviral efficiency increased ($p < 0.05$) when positive and negative air ions existed together (using the

Table 1
Overall filtration efficiency and pressure drop with ionizer and external electric field (numbers in parentheses are theoretically calculated values).

Duct velocity (m/s)	Filter		Filter + Ionizer		Filter + Ionizer + E-field	
	$\eta_{filtration}$(%)	Δp (Pa)	$\eta_{filtration}$(%)	Δp (Pa)	$\eta_{filtration}$(%)	Δp (Pa)
0.3	56.5 ± 1.2 (51.8)	13.3	63.5 ± 2.0 (57.3)	13.3	71.7 ± 0.6 (69.9)	13.3
0.5	48.9 ± 1.6 (41.2)	22.5	54.1 ± 2.8 (45.4)	22.5	57.8 ± 1.4 (53.9)	22.5
1.0	31.9 ± 1.9 (29.1)	46.0	36.9 ± 2.2 (31.6)	46.0	38.1 ± 1.5 (35.5)	46.0

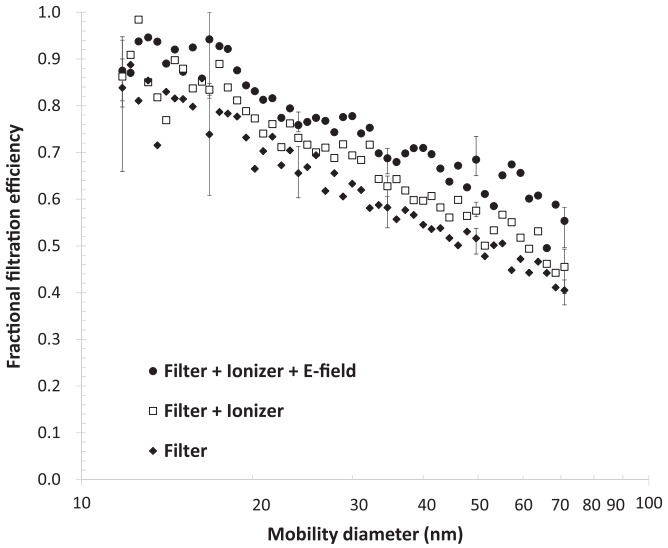

Fig. 5. Fractional filtration efficiency for duct velocity of 0.3 m/s.

bipolar mode ionizer). The antiviral efficiencies of bipolar air ions with total 10^7 ions/cm^3 concentration were 64.3, 89.1, and 96.4% with exposure times of 15, 30, and 45 min, respectively. The results imply that the chance of contact between the virus and air ions might increase when there were both positive and negative ions. Lee et al. (2014) performed an antibacterial test with air ions on aerosolized *Staphylococcus epidermidis*, which moved with a duct air flow. Their bipolar ion treatment affected the antibacterial efficiency, which increased as the number of charges in the ion polarity increased and the flow velocity decreased. Noyce and Hughes (2002) explained that electrostatic interactions with numerous charged groups in the cell wall could possibly induce a physiological change in the cell wall structure. Digel, Artmann, Nishikawa, Cook, Kurulgan, and Artmann (2005) reported that when negatively and positively charged ions were applied to test bacteria, after contact and sedimentation of the bipolar ions onto bacterial surfaces, hydroxyl radicals appeared in the cell wall as a result of chemical interactions between the positive ions and the negative ions. As a result of these reactions, the hydroxyl radicals damaged proteins and lipids (Nishikawa & Nojima, 2003).

While there have been reports on inactivation of airborne bacteria with ion emission, no report can be found on inactivation of airborne virus with ion emission, in open literatures. Instead of directly using ion emission, Wu et al. (2015) used atmospheric-

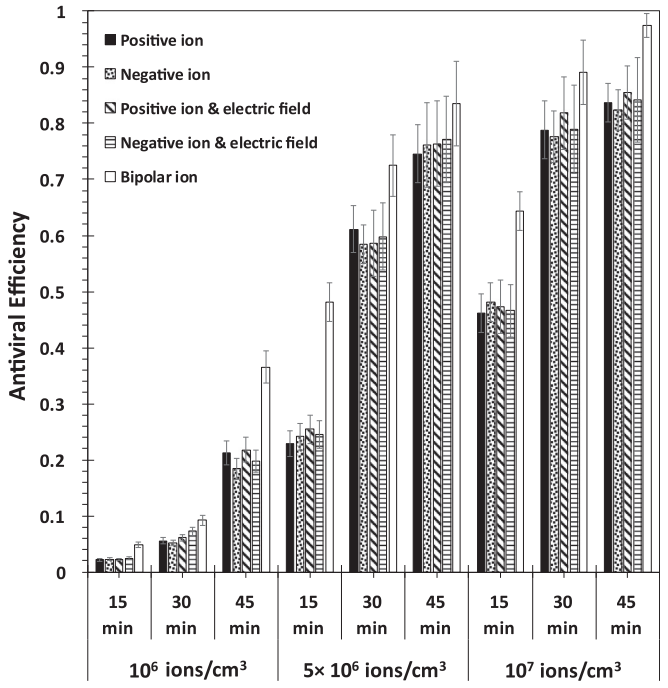

Fig. 6. Antiviral efficiency of air ions.

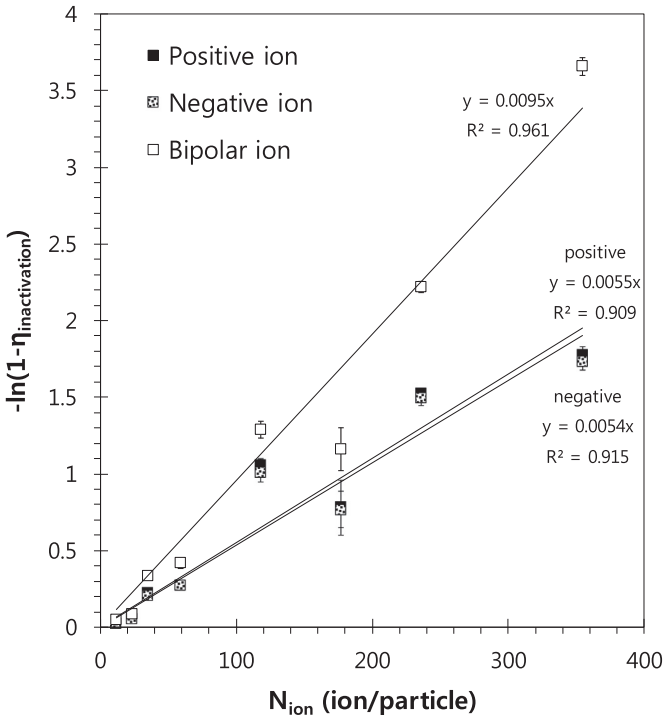

Fig. 7. Susceptibility constant of bacteriophage MS2 with air ions.

pressure cold plasma to inactivate airborne bacteriophage MS2. They explained that reactive oxygen species such as atomic oxygen, hydroxyl radicals caused the inactivation. They also showed that plasma treated sample had more fragments than non-exposed sample with scanning electron microscope images.

Fig. 6 also shows that the effect of an external electric field was not significant ($p > 0.05$). The electric-field strength used in this study was 2 kV/cm, but this value is far lower than that used by Yao et al. (2005), who studied the inactivation of bacteria with variations in the electric-field strength, polarity, exposure time, and bacterial species. In their study, 90% of *Pseudomonas fluorescens* was inactivated when an electric field of 15 kV/cm was applied for 30 min or longer.

Ozone was sampled at 90 mm downstream of the ionizer. The ozone concentration was 2~10 ppb when unipolar air ions were generated. When bipolar air ions were generated, the ozone concentration a little increased to 30 ppb. To study the effect of ozone on antiviral efficiency, we carried out additional experiments. After the ionizer was operated in a bipolar mode, all of the positive and negative air ions were eliminated using an ion trap with 20 V of applied voltage. Then the remaining ozone of 30 ppb concentration was carried by air flow to the test duct. When the virus particles captured in a filter were exposed to the ozone flow for 45 minutes, it was found that the antiviral efficiency of ozone was 4.52% which was much lower than that of bipolar ions (please remind that the antiviral efficiency was 96.4%, when the virus particles were exposed to both the ozone and bipolar ions for 45 minutes). De Mik and De Groot (1977) also observed that airborne phi X174 phage kept biological activity at an ozone concentration of 40 ppb and a contact time of 30 min.

Fig. 7 shows the susceptibility constants of the MS2 virus to air ions. The susceptibility constants were 5.5×10^{-3}, 5.4×10^{-3} and 9.5×10^{-3} for positive ion treatment, negative ion treatment, and bipolar ion treatment, respectively. The susceptibility constants can be used to determine how many air ions are required to achieve a target antiviral efficiency. For 90% of inactivation, the required numbers of air ions for single MS2 virus were 418, 426, and 239 for positive ion treatment, negative ion treatment, and bipolar ion treatment, respectively.

4. Conclusions

Laboratory tests involving the filtration and inactivation of a bacteriophage MS2 virus were conducted using a carbon-fiber ionizer installed upstream of a medium filter. The overall filtration efficiency increased when the ionizer was on, even though the average charge number resulting from the operation of the ionizer was less than 1. The antiviral efficiency with bipolar ions was higher than that with unipolar ions, but the electric field was not effective to inactivation. The susceptibility constant of the bacteriophage MS2 to air ions was presented and will be useful for comparison with the antimicrobial efficiencies of other microorganism species.

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