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Removal of submicron aerosol particles and bioaerosols using carbon fiber ionizer assisted fibrous medium filter media †

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Abstract

This paper reports the installation of a carbon fiber ionizer in front of a fibrous medium filter to enhance the removal of submicron aerosol particles and bioaerosols. Test particles (KCl) were classified with a size range of 50-600 nm using a differential mobility analyzer (DMA). The number concentration of the test particles was measured using a condensation particle counter (CPC). The average charge per particle was estimated by current measurements using an aerosol electrometer. At the face velocity of 0.5 m/s, the particle removal efficiency was 31.4% (for d_p=100 nm) when the ionizers were not operating but increased to 35.7% and 46.9% at 1.6×10^{11}ions/s and 6.4×10^{12}ions/s with the ionizers, respectively. For the antibacterial tests, the test bioaerosols (*E. coli*) were aerosolized using a nebulizer and were deposited on the filter media for 5 minutes. After the deposited bioaerosols were exposed to unipolar air ions, they were incubated for 12 hours. The survival efficiency of *E. coli* was measured using a colony counting method. The survival fractions of *E. coli* exposed to positive air ions for 1, 5 and 10 minutes were 61.7%, 45.4% and 25.2%, respectively.

Keywords: Submicron aerosol particle; Bioaerosols; Particle charging; Fibrous medium

1. Introduction

When humans inhale, particles in the air enter the body. Micron particles are intercepted by the hairs of the nostril, but submicron particles can reach the lung and deposit in the alveoli [1]. Bioaerosols are airborne particles with biological origins, including viruses, bacteria, fungi and a variety of living materials, and are known to be etiological agents of many diseases. Fibrous filters are used to remove these aerosol particles. However, it is difficult to remove submicron particles using fibrous filters [2], and the bioaerosol collected on fibrous filter surfaces can be cultivated and release bad odors [3].

It was proposed that the installation of an air ionizer in front of a fibrous medium filter will enhance the removal of submicron aerosol particles and bioaerosols. Continuous emission from an ionizer was found to increase the collection efficiency of a filter while not affecting the pressure drop, e.g. Lee et al. [4] for facepiece respirator filters and Agranovski et al. [5] for low-efficiency HVAC air filters. Huang et al. [6] examined the ion-induced enhancement effect on the filtration of a HVAC filter with biological aerosols, including aerosolized bacterial cells, bacterial and fungal spores, and viruses. Fletcher et al. [7] reported the antimicrobial by electroporation of positive and negative ions in air. Han et al. [8] examined a carbon brush type ionizer with an ion emission tip consisting of a bundle of micron sized carbon fibers. The carbon fiber ionizer produced stable unipolar ions in sufficiently high concentrations, without generating particulate matter and ozone.

This study examined the effect of a carbon fiber ion-

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izer on particle charging and particle capture on the media of a fibrous medium filter. Submicron sized aerosol particles were selected due to their relatively low charging and collection efficiencies compared to micro-sized aerosol particles. In addition, the effect of a carbon fiber ionizer on the inactivation of bioaerosols was studied.

2. Experimental method

The experiment system consisted of a test duct, a test particles (submicron particles and bioaerosols) generation system, and a measurement system. The test duct (cross sectional area of $0.04\times0.04m^2$, length of 1m) was made from acryl. The media of the medium filter composed of glass fibers was installed in the middle of the test duct. Table 1 lists the specifications of the filter media. Two sampling probes made from 6.5 mm stainless steel were located at the front and behind the filter media for aerosol sampling. A pair of carbon fiber ionizers was positioned on the top and bottom of the test duct, respectively, 10cm ahead of the filter media. Each ionizer consisted of an ion emission tip and a power pack. The ion emission tip consisted of a bundle containing 300±50 carbon fibers. The diameter of each carbon fiber was approximately 5-10 μm. The input voltage of the power pack was AC 220V, 60 Hz, and the maximum output voltage was peak-to-peak 4 kV, 60 Hz (saw tooth wave form). The operation voltage was controlled using a rheostat. The total power consumption was < 1W.

Table 1. Specifications of the filter media.

Size (mm^3)	Material	Fiber size	Solidity	Pressure drops (@0.5 m/s)
40×40×0.5	Glass fiber	10 μm	0.55	29 mmAq

The gaseous ion concentrations were measured using an ion counter (Air ion counter, AlphaLab, Inc., USA). A pressure gauge was used to measure the pressure decrease across the air filter media. An O_3 monitor (PortaSensII, Ati, USA) was used to monitor O_3, which might be produced by the carbon fiber ionizers. The temperature and relative humidity inside the test duct were 22.5±3°C and 10±5%, respectively.

2.1 Particle removal test

For the filtration tests, potassium chloride (KCl) particles were used as the test particles according to the ANSI/ASHRAE standard 52.2-2007 [9]. A steady state concentration of KCl particles was supplied to the test duct. A branch of particle free compressed air from a dry-cleaned air supply system consisting of an oil trap, diffusion dryer and HEPA (high efficiency particulate air) filter was delivered to a Collison type atomizer of a solution containing KCl 5-10 Wt.% (in water) to generate the test particles. The test particles from the atomizer were passed through a diffusion dryer for water removal followed by a charge neutralizer (Soft X-ray charger 4530, HCT Co., Ltd., Korea)

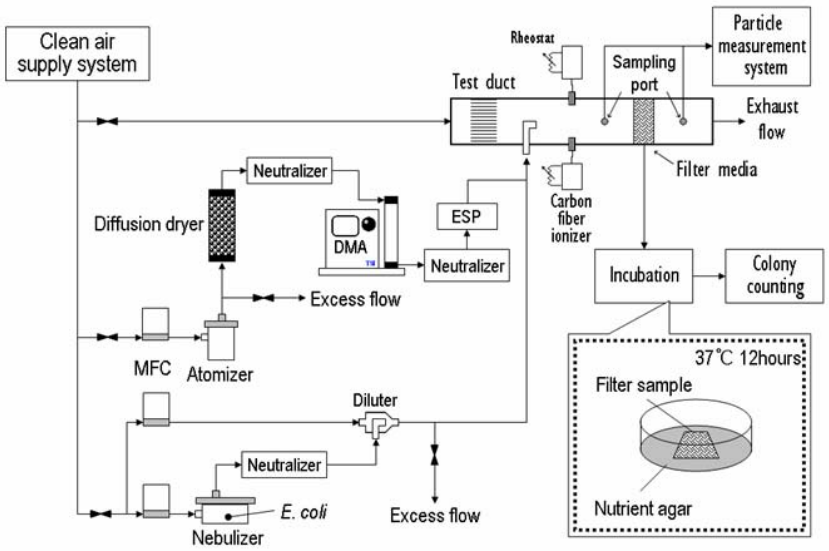

Fig. 1. Experimental setup.

to realize a Boltzmann charge distribution. The test particles from the neutralizer were analyzed using a differential mobility analyzer (DMA; 3080, TSI, USA) and classified to the required size of 50, 100, 200, 300, 400, 500, and 600 nm. The monodisperse particles with natural charges were passed through another neutralizer (Soft X-ray charger 4530, HCT Co., Ltd., Korea) for charge neutralization and an electrostatic precipitator (ESP), where an average electric field of 5 kV/cm was used to remove the charged particles and deliver uncharged particles to the test duct. The desired concentrations of the test particles were controlled using a laminar flow meter (LFM). Another branch of clean air was also delivered to the test duct and mixed with the particle-laden air flow. The mixture flow rate was maintained 48 ℓ/min in order to achieve a face velocity at the filter media of 0.5 m/s. The total number concentration of the test particles was measured using a condensation particle counter (3776, TSI, USA) with a sampling air flow rate of 0.3 ℓ/min. The average charge per particle was estimated by current measurements using an aerosol electrometer (3068A, TSI, USA). The air was sampled at an air flow rate of 5 ℓ/min using a vacuum pump. The sampled air flow was passed through an ion trap, where an average electric of 100V/cm was applied to eliminate the gaseous ions. The average charge per particle (n) was then calculated using the following equation:

$$n = I/(N \cdot Q \cdot e) \quad (1)$$

where N is the particle number concentration, I is the current, Q is the sampling flow rate, and e is the elementary unit of charge (= 1.6×10^{-19} coulomb).

2.2 Antimicrobial test

E. coli was used as the test bioaerosol particles according to the ISO 14698-1:2003 [10]. Particle free compressed air at a pressure of 5psi and a flow of 2 ℓ/min entered the nebulizer and aerosolized *E. coli*. The aerosolized *E. coli* was passed through a neutralizer (Soft X-ray charger 4530, HCT Co., Ltd., Korea) to give a Boltzmann charge distribution, and diluted in particle free air at a flow rate of 7.6 ℓ/min. From this mixture, a flow of 3 ℓ/min was supplied to the test duct, and the bioaerosols were deposited on the filter media over a 5 minute period. A sample of the deposited bacteria (sample #1) was exposed to ion free clean air for 10 minutes to evaluate the level of dehydration of bacteria by air. The other sample (sample #2) was then exposed to ion free clean air for 9 minutes after exposing the sample to positive air ions for 1 minute. Sample #3 was then exposed to air ions for 5 minutes and ion free air for 5 minutes. Sample #4 was exposed to only air ions for 10 minutes. Each sample was attached to a nutrient agar plate that was incubated at 37°C for 12 hours. The number of bacteria was measured using a colony counting method.

3. Results and discussion

3.1 Particle removal test

When the aerosol particles passed through a filter media, the number concentration of the test particles decreased as a result of filtration. The fractional particle removal efficiency, $\eta_p(d_p)$, was defined using the following equation:

$$\eta_p(d_p) = 1 - \frac{C_{downstream}(d_p)}{C_{upstream}(d_p)} \quad (2)$$

where $C(d_p)$ is the number concentration of test particles with size d_p. The upstream number concentration, $C_{upstream}(d_p)$, was fixed to 5000±100 particles/cm^3 for each particle size, d_p. Fig. 2 shows the results with and without the carbon fiber ionizers when the face velocity at the test duct was 0.5 m/s. In the case where no ionizers were used, Fig. 2 shows the theoretical efficiency of the filter media defined using the following equation [2],

$$\eta(d_p) = 1 - \exp\left(-\frac{4\alpha L E(d_p)}{\pi d_f (1-\alpha)}\right) \quad (3)$$

where L is the filter thickness, α is the filter solidity and d_f is the fiber diameter. The single fiber (fractional) removal efficiency $E(d_p)$ was defined as

$$E(d_p)=1-\{1-E_{diff}(d_p)\}\times\{1-E_{int}(d_p)\}\times\{1-E_{imp}(d_p)\} \quad (4)$$

The removal efficiency due to Brownian diffusion is given by the equation reported by Hinds [2] as follows:

$$E_{diff}(d_p) = 2Pe^{-2/3} \quad (5)$$

where Pe is the Peclet number (=$d_f \cdot u_0/D$), and D is the diffusion coefficient depending on the particle size d_p.

The face velocity at the fiber of filter (u_0) is defined as follows:

$$u_0=U/(1-\alpha) \tag{6}$$

where U is the face velocity at the test duct. According to Lee and Liu [11], the removal efficiency due to interception is given by

$$E_{\text{int}}(d_p)=0.6\times\frac{(1-\alpha)}{h_k}\times\frac{R^2}{1+R} \tag{7}$$

where $R=d_p/d_f$. The Kuwabara hydrodynamic factor (h_k) is defined as

$$h_k=-\frac{\ln\alpha}{2}-\frac{3}{4}+\alpha-\frac{\alpha^2}{4} \tag{8}$$

The removal efficiency due to inertial impaction is given by the following equation [12]

$$E_{imp}(d_p)=\frac{Stk^3}{(Stk^2+0.77Stk+0.22)} \tag{9}$$

where Stk is the Stokes number defined as

$$Stk=\frac{\rho_p d_p^2 u_0}{18\mu d_f} \tag{10}$$

where ρ_p is the particle density and μ is the air viscosity.

The results in Fig. 2 show that approximately 100 nm is most penetration particle size (MPPS) of the filter media. In all experimental cases, the particle removal efficiencies increased when the particle size was larger or smaller than 100 nm. The theoretical results with no air ions (filter media only) agreed well with the experimental results. The particle removal efficiency was 31.4% (for d_p=100 nm) when the ionizers were not operating but increased to 35.7% and 46.9% at 1.6×10^{11} ions/s and 6.4×10^{12} ions/s with the ionizers, respectively. Higher concentrations of air ions increase the probability of collisions between ions and particles, resulting in higher particle charging.

In these tests, the average charge per particle of various particle sizes were measured, and the results are shown in Fig. 3. The average charge number increased with increasing ion generation rate. Fig. 3

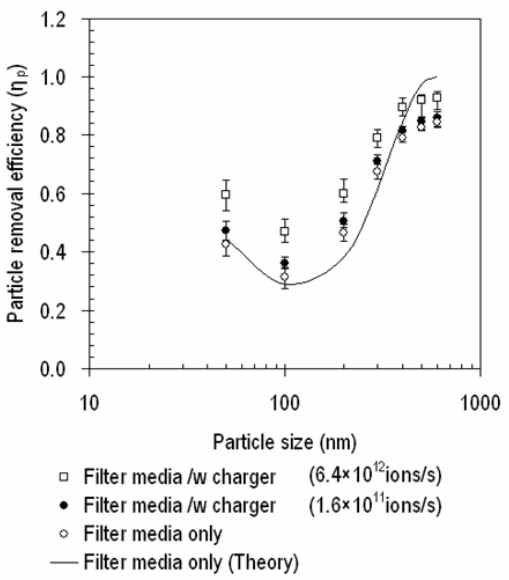

Fig. 2. Particle removal efficiencies as a function of the particle size.

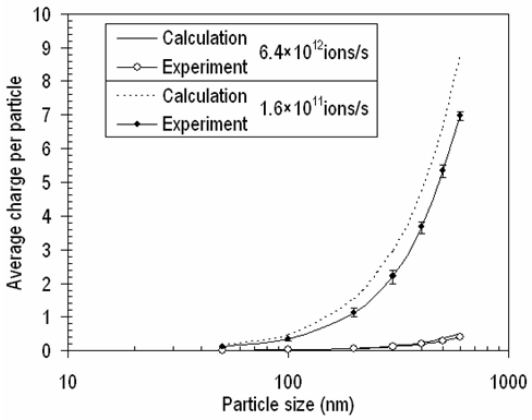

Fig. 3. Average charges per particle as a function of the particle size.

also shows the calculation results, which agreed with the experimental data. Considering only a diffusional charging mechanism, the theoretical average number of charges per particle with respect to the charging time t, is defined as follows [2]

$$n(d_p)=\frac{d_p kT}{2e^2}\ln\left[1+\frac{\pi d_p c_i e^2 N_i t}{2kT}\right] \tag{11}$$

where c_i is the mean thermal speed of air ions (2.4×10^4 cm/s at 298K) and N_i is the concentration of ions per particle. The Boltzmann constant k is

Table 2. Information of calculation parameters.

Symbol	Parameter	Value
L	filter thickness	0.5 mm
U	face velocity (duct)	0.5 m/s
u_0	face velocity (filter fiber)	1.11 m/s
ρ_p	particle density	1.987 g/cm^3
μ	air viscosity.	1.81×10^{-5} kg/ms
c_i	mean thermal speed of air ions	2.4×10^4 cm/s
k	Boltzmann constant	1.381×10^{-16} erg/K
t	charging time	0.2 sec

1.381×10^{-16} erg/K, d_p is the particle diameter, and T is the temperature. Charging time t (0.2 sec) is the ratio between the charging section (10 cm) and the face velocity (0.5 m/s). Information of the parameters for calculation is documented in Table 2.

Charged particles are captured by a combination of mechanical (impaction, interception and diffusion) and image forces. Air ions with high mobility are captured by the fibers, which creates a macroscopic electric field. The latter affects the motion of charged particles as well as the particle motion inside the filter structure. Unipolar charged particles that approach the filter surface are affected by two forces acting in opposite directions: drag and Coulomb's repelling force. The difference in these forces would cause some particle deceleration in the vicinity of the filter face [5]. Therefore, the residence time of charged particles across the filter media increases, resulting in higher removal efficiency, as demonstrated in Fig. 2.

Particle wall losses by the carbon fiber ionizers were < 4%. The ozone concentration was below the detection limit (under 0.01ppm) when the carbon fiber ionizers were on.

3.2 Antimicrobial test

Fig. 4 shows the survival fraction of the bioaerosols as a function of the ion exposure time. The survival efficiency was defined using the following equation:

$$Survival\ efficiency = \frac{CFU_{air\,ions}}{CFU_{clean\,air}} \tag{12}$$

where the numerator is the colony forming unit of *E. coli* when exposed to air ions and the denumerator is the colony forming unit in clean air. When the ion exposure time was increased, the survival efficiency

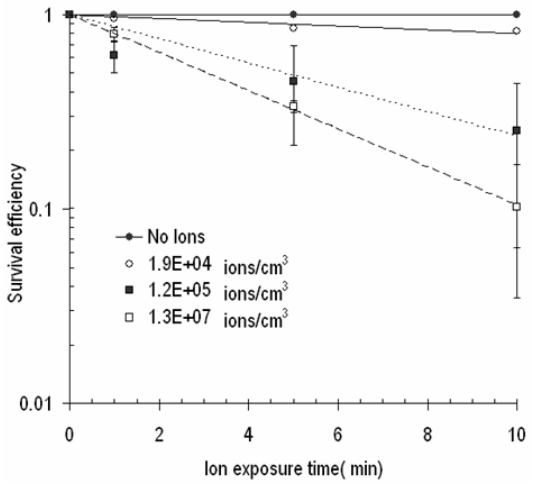

Fig. 4. Survival efficiency of *E. coli*.

decreased to 95.9, 85.6 and 82.0% at 1, 5, and 10 minutes, respectively (for an ion concentration of 1.9×10^4 ions/cm^3). When the ion concentrations were increased, the survival efficiencies at 1, 5, and 10 minutes decreased to 79.5, 33.6 and 10.2% (1.2×10^5 ions/cm^3) and 61.7, 45.4 and 25.2% (1.3×10^7 ions/cm^3), respectively.

4. Conclusions

This study examined the effects of a carbon fiber ionizer on particle charging and particle capture on the media of a fibrous medium filter as well as on the inactivation of bioaerosols. At the face velocity of 0.5 m/s, the particle removal efficiency was 31.4% (for d_p=100 nm) when the ionizers were not operating but increased to 35.7% and 46.9% at 1.6×10^{11}ions/s and 6.4×10^{12} ions/s with the ionizers, respectively. For the antibacterial tests, the test bioaerosols (*E. coli*) were aerosolized by a nebulizer and deposited on the filter media for 5 minutes. The deposited bioaerosols were exposed to unipolar air ions and incubated for 12 hours. The survival efficiencies of *E. coli* were measured using a colony counting method. When the ion exposure time was increased, the survival efficiency decreased to 95.9, 85.6 and 82.0% at 1, 5 and 10 minutes, respectively (for an ion concentration of 1.9×10^4 ions/cm^3). On the other hand, when the ion concentrations were increased, the survival efficiencies at 1, 5, and 10 minutes decreased to 79.5, 33.6 and 10.2% (1.2×10^5 ions/cm^3) and 61.7, 45.4 and 25.2% (1.3×10^7 ions/cm^3), respectively.

A carbon brush type ionizer can be applied to any filter to enhance fine particle removal with antimicrobial effects because it does not generate ozone and has low power consumption.

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