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Removal and retention of viral aerosols by a novel alumina nanofiber filter

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\textbf{ABSTRACT}

Nanomaterial, due to its unique physical, chemical and biological properties compared to its bulk counterparts, has the potential to provide a product superior to its bulk predecessor. In this study, a novel alumina nanofiber filter was assessed for its removal and retention capability for MS2 aerosol. Its physical removal efficiency in the 10–400nm range was 94.35%, while its viable removal efficiency was 98.87%, which was slightly lower than three conventional HEPA filters tested. However, its pressure drop was much lower than HEPA filters, yielding a higher filter quality than HEPA filters. The average extracted fraction from the nanofiber filter was \(8.64 \times 10^{-2} \pm 7.00 \times 10^{-2}\), which is three orders lower than another HEPA filters, demonstrating that the viruses were effectively retained in the nanofiber filter. Furthermore, the performance of the nanofiber filter showed no dependence on relative humidity. In conclusion, this novel alumina nanofiber filter presents advantageous potential for removal and retention of viral aerosol agents.

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\section{1. Introduction}

Bioaerosols are aerosols of biological origins such as viruses, bacteria, fungi, spores, pollen and allergens (Hinds, 1999). They can cause adverse health and welfare effects, including allergy, asthma, respiratory illnesses, crop damage and animals infection. The spread of airborne pathogens such as severe acute respiratory syndrome (SARS) and avian flu as well as the potential of intentional release of biological agents by terrorists such as the Anthrax in 2001 have raised the public’s concerns about bioaerosols and protection measures (Kortepeter & Parker, 1999; Rengasamy, Zhuang, & BerryAnn, 2004; Lee et al., 2008).

Filtration is one of the most commonly applied methods for aerosol removal because it is simple and economical. However, there are two main issues associated with filtration: (1) High aerosol removal efficiency is achieved only at the cost of high pressure drop, which is translated into high energy consumption for collective protection or high breathing resistance for individual protection. How to increase efficiency while maintaining low pressure drop is a critical challenge to filter development. (2) Collected biological agents may creep through the filter and reaerosolize. The reaerosolization may impose hazards to the person intended to protect. How to effectively retain the biological agents loaded on the filter, hence, is an important consideration (Ratnesar-Shumate et al., 2008; Rengasamy et al., 2004).

Nanofibrous media have the potential to solve the above issues due to their high surface area and ability to incorporate special functional groups at the nanoscale level (Barhate & Ramakrishna, 2007). A large surface-area-to-volume ratio of nanofiber can increase the probability of aerosol deposition on the fiber surface by diffusion and improve the filter efficiency (Ahn et al., 2006; Huang, Zhang, Kotaki, & Ramakrishna, 2003). Their smaller meshes can significantly increase the removal efficiency of
submicrometer particles by direct interception (Podgórski, Balazy, & Gradoń, 2006). Due to the slip on the nanofiber surface, the drag force on the nanofiber is smaller than in a non-slip flow, which translates into a lower pressure drop than conventional filters (Kosmider & Scott, 2002).

Most microorganisms have an electronegative surface due to their carboxyl and phosphate groups (Mozes et al., 1987; Valegård, Liljas, Fridborg, & Unge, 1990). Thus, an electropositive surface has the potential to have enhanced bioaerosol removal. This electrostatic attraction has been well demonstrated in aqueous environment. For example, iron oxyhydroxide floc particles have been investigated for adsorbing negatively charged MS2 viruses in water (Zhu, Clifford, & Chellam, 2005). Coating of sand and granular activated carbon with iron aluminum hydroxide increased the zeta potential and therefore improved virus removal (Scott et al., 2002). On the same basis, nanofibrous media can also be fabricated with electropositive surface to attract microorganisms.

A novel alumina nanofiber filter has been developed recently that has demonstrated ability to remove microbiological agents in aqueous environment using electrostatic attraction (Tepper & Kaledin, 2005). Although there has been no assessment in the aerosol phase yet, its feature is expected to have enhanced bioaerosol collection and retention efficiency that utilizes the above addressed advantages: large surface-area-to-volume ratio, lower pressure drop and higher surface charge density. The objective of this study was therefore to evaluate the performance of the alumina nanofilter for removal and retention of viral aerosols.

Experiments were conducted to assess the filter’s physical removal efficiency (PRE), viable removal efficiency (VRE), extracted fraction (EF) and filter quality (qF). Three conventional filters (two glass fiber filters and one PTFE filter) were also tested for comparison. In addition, the nanofiber filter was examined in three different relative humidities (RHs) to determine its response to different environmental conditions.

2. Experimental method

2.1. Test agent

MS2, an Escherichia coli bacteriophage, (ATCC® 15597–B1 ™ ) was chosen as the biological test agent. It has a single-stranded RNA genome and an approximate diameter of 28 nm (Golmohammadi, Valegård, Fridborg, & Liljas, 1993; Prescott, Harley, & Klein, 2002). MS2 is hydrophilic and electronegative in water (Valegård et al., 1990). It infects only male E. coli bacteria by injection of its RNA and A-protein. Due to the similar physical characteristics, it has been frequently used as a surrogate for mammalian viruses (Aranha-Creado & Brandwein, 1999). Freeze-dried MS2 bacteriophage was suspended with filtered deionized (DI) water to the concentration of \(10^8–10^9\) PFL/mL, which was the virus stock suspension.

2.2. Test filters

The test nanofiber filter consists of a single layer of alumina nanofiber grafted to a microglass fiber backbone. SEM and TEM images of fresh nanofiber filter are shown in Figs. 1a and c. The diameter of the alumina nanofiber is approximately 2–4 nm and its surface area is 450–600 m²/g (Tepper & Kaledin, 2005). Its composition has been identified as boehmite (AlOOH) by X-ray diffraction patterns and the zeta potential is +50 mV at pH 7. The filter is 800 μm thick with 92% porosity. The pore size for water filtration is 2 μm while for air use is 28 μm to allow for higher permeability. Its composition, synthesis and characteristics are defined as sample AF16 in Tepper and Kaledin (2007). This structure is different from other nanofibers tested for air filtration; their nanofiber diameters are in the 80–400 nm range (Ahn et al., 2006; Kosmider & Scott, 2002; Yun et al., 2007).

Three commercially available HEPA filters were also compared in the study: a 790-μm thick glass fiber filter (A) with resin binder, 1.0 μm pore size and 90% porosity (Millipore, AP1504700); a 78-g/m² basis weight HEPA glass fiber filter (B) that has 99.982% DOP collection efficiency (Lydall, grade 4450-HS); a 152-μm thick PTFE membrane filter (polytetrafluoroethylene with polytetrafluoroethylene support, Zefluor membrane) with a 2.0-μm pore size (Pall, P5PJ047).

2.3. Experimental system

Fig. 2 shows a schematic drawing of the experimental system. The bioaerosol was generated by a six-jet Collison nebulizer (Model CN25, BGI Inc., Waltham, MA) and passed through a dilution drier to remove the moisture. The virus concentration in the nebulizer was around \(10^7\) PFU/mL and was prepared by diluting 0.1 mL of virus stock suspension in 50 mL of sterile DI water. The corresponding MS2 aerosol concentration was approximately \(10^8\)–\(10^9\) PFL/mL, which was the virus stock suspension. The temperature and humidity of the air stream were measured by a thermometer and a RH meter (Model HX94C, OMEGA Engineering Inc., Stamford, CT), respectively. The airflow was then divided into two parallel streams. One stream that contained the test filter was designed for experimental collection while the other, which had no test filter, served as the control. The bioaerosol was collected by a biosampler (SKC Inc., Eighty-Four, PA) that had 15 mL of phosphate buffer solution (PBS) as collection liquid. MS2 collected in the biosampler was then enumerated following the procedures in Adams (1959) and plates were incubated at 37 °C for 18 h. The experiment was conducted at 22 ± 2 °C and 50 ± 5% RH for 30-min intervals, and the face velocity of filtration was 26.0 cm/s. In addition, the nanofiber filter was tested in three RHs (35%, 50% and 75%) to determine its response to different environmental conditions. RH was regulated by controlling the ratio of dry cylinder air to the nebulizer flow. The pressure drop of the test filter was measured using a pressure gauge (2010AV C, Dwyer Instruments, Michigan City, IN).
2.4. Removal efficiency

In this study, two types of efficiency ($\eta$) were determined: VRE and PRE. The efficiency was determined by comparing the penetrating viral aerosols in the experimental stream and the feed viral aerosols in the control stream. VRE was determined from the number of plaque-forming units (PFUs) on the petri dish for each collection stream following Eq. (1):

$$\eta \text{ (VRE or PRE)} = 1 - \frac{N_p}{N_c}$$  \hspace{1cm} (1)

where $N_c$ is the number of viral aerosols entering the filter and $N_p$ is the number of viral aerosols penetrating the filter. Regarding PRE, the particle size distributions (PSDs) of the aerosols entering and penetrating the test filters were measured by a scanning mobility particle sizer (SMPS, Model #3936, TSI) and the PRE was calculated according to Eq. (1) based on the SMPS measurements. It should be noted that the freeze-dried MS2 from ATCC contains non-MS2 content, e.g. protein. Hence, the SMPS was measuring particles containing MS2 virons rather than purely MS2 virons.
2.5. Extracted fraction

After 2 h of the experiment for removal efficiency, the test filter was removed from the filter holder and subjected to vortex mixing (Model # M16715, Barnstead) to extract the MS2 collected on the filter. After various vortexing times (0, 1, 3 and 5 min), the infectivity of MS2 in the vortexing solution was analyzed and expressed as EF, as defined by Eq. (2):

\[ EF = \frac{N_{\text{Ext}}}{N_{\text{Coll}}} \]

where \( N_{\text{Ext}} \) is the MS2 count extracted from the filter and \( N_{\text{Coll}} \) is the MS2 count of control collection (MS2 collected by the biosampler without nanofiber filter) minus the count of experimental collection (penetrating MS2 collected by the biosampler with nanofiber filter).

3. Result and discussions

3.1. PSDs and removal efficiencies

The PSDs measured by the SMPS are shown in Fig. 3. The mode size of the feed aerosol was about 30 nm, which is similar to the size of a single MS2 virus and agrees well with prior studies using MS2 (Burton, Grinshpun, & Reponen, 2007; Hogan et al., 2005; Richardson, Eshbaugh, Hofacre, & Gardner, 2006). The PSDs of penetrating aerosol from the four filters are also shown in Fig. 3a. The most penetrating aerosol size was around 100 nm, which is smaller than the 0.3-μm standard that is commonly used in filter testing (NIOSH, 2005) (Fig. 3b). The corresponding minimum PRE of the nanofiber filter for 100 nm was around 75%, which is lower than other HEPA filters tested. Compared to other filters tested for MS2 aerosol reported in the literature,

![Fig. 3. (a) Particle size distributions of MS2 before and after the filters and (b) PRE of MS2 in the 10–400 nm particle size range.](image-url)
**Physical removal efficiency, viable removal efficiency, pressure drop, filter quality and extracted fraction for nanofiber filter, glass fiber filters A, B and PTFE filter.**

| Filters        | PRE (%) | VRE (%) | $\Delta P$ (in H$_2$O)$^b$ | $q_p$ (kPa)$^c$ | $q_v$ (kPa)$^d$ | EF       |
|----------------|---------|---------|-----------------------------|-----------------|-----------------|----------|
| Nanofiber      | 94.35 ± 3.22 | 98.87 ± 0.78 | 2.5–2.8 | 6.43 | $8.64 \times 10^{-2}$ ± $7.00 \times 10^{-2}$ |
| Glass fiber A  | 99.99 ± 0.001 | 99.92 ± 0.14 | 15–16 | 2.31 | 1.79 | 162 ± 61 |
| PTFE           | 96.02 ± 2.27 | 99.94 ± 0.05 | 6.0–6.5 | 4.97 | 38.1 ± 1.5 |
| Glass fiber B  | 99.63 ± 0.22 | 99.96 ± 0.01 | 5.0–5.5 | 5.72 | 32.2 ± 9.8 |

*Overall efficiency over 10–400 nm.

*Measured at 26.0 cm/s face velocity.

*Based on PRE.

*Based on VRE.

The pressure drop measurements for the nanofiber filter along with three HEPA filters (Table 1). As shown, the nanofiber filter’s VRE was slightly lower than the other filters. The difference between PRE and VRE implies that the virus distribution does not follow the number size distribution of the aerosol (Hogan et al., 2005), although no detailed information regarding virus distribution in aerosol is available yet. SEM and TEM images of nanofiber filters after the MS2 filtration experiment and vortexing extraction are shown in Figs. 1b and d. Compared to those before the MS2 experiment, it is clear to observe particles trapped on the fiber surface.

There are other reasons why the PRE and VRE are not comparable. First, the sampling particle size range is different. SMPS only covers from 10 to 400 nm while the biosampler has no size limit. However, the biosampler has very low collection efficiency in the ultrafine range (Hogan et al., 2005), even as low as 10%. On the other hand, the SMPS also has limitation of low charging efficiency and has to rely on assumed Boltzmann charge distribution for correction.

### 3.2. Pressure drop and filter quality

The pressure drop measurements for the nanofiber filter along with three HEPA filters are displayed in Table 1. As shown, the pressure drop of the nanofiber filter was much lower than the other three filters. Due to the slip on the nanofiber surface, the drag force on the nanofiber is smaller than in a non-slip flow, which translates into a lower pressure drop (Kosmider & Scott, 2002). In comparison, the glass fiber filter A as an analytical filter had the highest pressure drop.

Combining penetration and pressure drop, filter quality ($q_F$) can be calculated by the following Eq. (3) (Hinds, 1999):

$$q_F = \ln(1/p)/\Delta P$$

where $p$ is penetration, and $\Delta P$ is pressure drop. A filter with better quality has less penetration for the same pressure drop compared to other filters. The results for all four filters are listed in Table 1. As shown, based on PRE, the nanofiber filter has the best filter quality than other filters. It’s 1.9 times higher than the PTFE filter. For measured VRE, the nanofiber filter still presents the best filter quality, which is 3.3 times higher than the glass fiber filter A. This is mainly contributed by its unique feature of low pressure drop. Similar improvement in filter quality by decreasing fiber diameter was reported by Podgórski et al. (2006), who reported that their nanofiber layer was 2.6 times better than two layers of microfibrous support although it was much thinner. Yun et al. (2007) also reported similar observations.

### 3.3. Extracted fraction

The results of EFs for all filters are listed in Table 1. As shown, the average EF of the nanofiber filter over 1, 3, and 5 min of vortexing time was $8.64 \times 10^{-2}$ ± $7.00 \times 10^{-2}$, which was significantly lower than any other compared filters. This phenomenon indicates that viruses were effectively retained in the nanofiber filter, due to electrostatic attraction between the electropositive fiber surface and electronegative MS2 particles. In contrast, the EFs of the other three filters were all greater than one. Theoretically, the EF should be less than one. However, the feed MS2 concentration determined by the biosampler collection was an underestimate because the biosampler had low collection efficiency for nanometer particles (< 10% for 30–100 nm; Hogan et al., 2005). With effective extraction, the EF therefore can be great than one. Unfortunately, there is no existing bioaerosol sampling method that allows better viable sampling and liquid impingement is the commonly accepted method (Hogan et al., 2005; Wang & Brion, 2007). Therefore, it was used in this study.

The filter’s unique feature of electrostatically attracting viruses provides the capacity to retain viruses. The isoelectric point of MS2 is pH 3.9 and thus the MS2 is electronegative above this value (Ackermann & Dubow, 1987; Zhu et al., 2005). On the other hand, the zeta potential of nanofiber media is +5.0 mV at pH 7 (Tepper & Kaledin, 2007). To further verify the electrostatic attraction, experiments were carried out with four fresh filters added to a suspension of known MS2 concentration (~$10^7$ PFU/mL) and the suspension was vortexed for up to 10 min. The results are shown in Fig. 4. The infectivity of MS2 on the nanofiber filter decreased dramatically with an increase in vortexing time. In contrast, the infectivity of MS2 on the other three filters had a
similar decay as in DI water for all vortexing times. The difference further verifies the effect of electrostatic attraction exerted by the alumina nanofiber filter.

3.4. Performance under different RHs

The VRE of the nanofiber filter tested at 35%, 50% and 75% RH were 98.13 ± 1.32%, 98.87 ± 0.78% and 98.79 ± 0.62%, respectively. Apparently, the performance of the nanofiber was not affected by RH change. It has been reported that high RHs decrease the removal efficiencies of electret filters (Motyl & Lowkis, 2006; Moyer & Stevens, 1989; Raynor & Chae, 2004; Yang et al., 2007) due to the reduction of charges within the filter. For non-electret filters that rely on mechanical removal mechanisms, RH imposes no significant effect on the removal (Huang & Yang, 2006; Kim, Bao, Okuyama, Shimada, & Niinuma, 2006). Wang and Brion (2007) showed that glass microfiber filter had similar performance at 23% and 50% RHs after the filter had reached a steady-state condition. Compared to electrets where the charge is induced during manufacture, the nanofiber’s charge is intrinsic in the way the alumina is formed. Hence, the charge is not water sensitive and is retained in bulk water.

4. Conclusions

This novel alumina nanofiber filter has demonstrated potential for effective removal and retention of MS2 aerosol. It presented lower PRE and VRE than conventional HEPA filters, but its pressure drop was much lower due to smaller drag force on the nanofiber surface. Hence, the nanofiber filter presented the best filter quality. The EF of nanofiber filter was three orders lower than the HEPA filters, demonstrating that viruses were effectively retained in the nanofiber filter due to electrostatic attraction. While the performance of conventional electret filters decreases at higher RHs, different RHs imposed no effects on the nanofiber filter’s ability to remove aerosol.

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References

Ackermann, H. W., & Dubow, M. S. (1987). *Viruses of prokaryotes*. Boca Raton, FL: CRC Press.

Adams, M. H. (1959). *Bacteriophages*. New York: Interscience.

Ahn, Y. C., Park, S. K., Kim, G. T., Hwang, Y. J., Lee, C. G., Shin, H. S. et al. (2006). Development of high efficiency nanofilter made of nanofibers. *Current Applied Physics*, 6, 1030–1035.

Aranha-Creado, H., & Brandwein, H. (1999). Application of bacteriophages as surrogates for mammalian viruses: A case for use in filter validation based on precedents and current practices in medical and environmental virology. *PDA Journal of Pharmaceutical Science and Technology*, 53, 75–82.

Barhate, R. S., & Ramakrishna, S. (2007). Nanofibrous filtering media: Filtration problems and solutions from tiny materials. *Journal of Membrane Science*, 296, 1–8.

Burton, N. C., Grinshpun, S. A., & Reponen, T. (2007). Physical collection efficiency of filter materials for bacteria and viruses. *Annals of Occupational Hygiene*, 51, 143–151.
Golmohammadi, R., Valegard, K., Fridborg, K., & Liljas, L. (1993). The refined structure of bacteriophage MS2 at 2.8 angstrom resolution. *Journal of Molecular Biology*, 234, 620–639.

Hinds, W. C. (1999). *Aerosol technology*. New York: Wiley.

Hogan, C. J., Kettleson, E. M., Lee, M. H., Ramaswami, B., Angenent, L. T., & Biswas, P. (2005). Sampling methodologies and dosage assessment techniques for submicrometre and ultrafine virus aerosol particles. *Journal of Applied Microbiology*, 99, 1422–1434.

Huang, H.-L., & Yang, S. (2006). Filtration characteristics of polysulfone membrane filters. *Journal of Aerosol Science*, 37, 1198–1208.

Huang, Z. M., Zhang, Y. Z., Kotaki, M., & Ramakrishna, R. (2001). A review on polymer nanofibers by electrospinning and their applications in nanocomposites. *Composites Science and Technology*, 63, 2223–2253.

Kim, C. S., Bao, L., Okuyama, K., Shimada, M., & Niinuma, H. (2006). Filtration efficiency of a fibrous filter for nanoparticles. *Journal of Nanoparticle Research*, 8, 215–221.

Kortepeter, M. G., & Parker, G. W. (1999). Potential biological weapons threats. *Emerging Infectious Diseases*, 5, 523–527.

Kosmider, K., & Scott, J. (2002). Polymeric nanofibers exhibit an enhanced air filtration performance. *Filtration & Separation*, 39, 20–22.

Lee, J. H., Wu, C. Y., Wysocki, K., Farrah, S., & Wander, J. (2008). Efficacy of iodine-treated biocidal filter media against bacterial spore aerosols. *Journal of Applied Microbiology*, 105, 1318–1326.

Morty, E., & Lowkis, B. (2006). Effect of air humidity on charge decay and lifetime of PP electret nonwovens. *Fibres & Textiles in Eastern Europe*, 14, 39–42.

Moyer, E. S., & Stevens, G. A. (1989). "Worst case" aerosol testing parameters: II. Efficiency dependence of commercial respirator filters on humidity pretreatment. *American Industrial Hygiene Association Journal*, 50, 265–270.

Mozes, N., Marchal, F., Hersmes, M. P., Van Haecht, J. L., Reuliaux, L., Leonard, A. J., et al. (1987). Immobilization of microorganisms by adhesion: Interplay of electrostatic and nonelectrostatic interactions. *Biotechnology and Bioengineering*, 30, 439–450.

NIOSH. (2005). *Determination of particulate filter penetration to test against liquid particulates for negative pressure, air-purifying respirators standard testing procedure (STP)*. Procedure No. RCT-APR-STP-0051, 0052, 0053, 0054, 0055, 0056, Revision 1.1. National Institution for Occupational Safety and Health, National Personal Protective Technology Laboratory. Pittsburgh, PA: US.

Podgórski, A., Balazy, A., & Gradoń, Ł. (2006). Application of nanofibers to improve the filtration efficiency of the most penetrating aerosol particles in fibrous filters. *Chemical Engineering Science*, 61, 6804–6815.

Prescott, L. M., Harley, J. P., & Klein, D. A. (2002). *Microbiology*. 5th ed, New York: McGraw-Hill.

Ratnesar-Shumate, S., Wu, C. Y., Wander, J., Lundgren, D., Farrah, S., Wanakule, P., et al. (2008). Evaluation of physical capture efficiency and disinfection capability of a novel iodinated filter medium. *Aerosol and Air Quality*, 8, 1–18.

Raynor, P., & Chae, S. (2004). Long-term performance of electrically charged filters in a ventilation system. *Journal of Occupational and Environmental Hygiene*, 1, 463–471.

Reinsaamy, A., Zhuang, Z., & BerryAnn, R. (2004). Respiratory protection against bioaerosols: Literature review and research needs. *American Journal of Infection Control*, 32, 345–354.

Richardson, A. W., Eshbaugh, J. P., Hofacre, K. C., & Gardner, P. D. (2006). Respirator filter efficiency testing against particulate and biological aerosols under moderate to high flow rates. Report No. ECBC-CR-085. Edgewood Chemical and Biological Center, US Army Research.

Scott, T. M., Sabo, R. C., Lukasik, J., Boice, C., Shaw, K., Barroso-Giachetti, L., et al. (2002). Performance and cost-effectiveness of ferric and aluminum hydrous metal oxide coating on filter media to enhance virus removal. *KONA*, 20, 159–167.

Tepper, F., & Kaledin, L. (2007). *Electrostatic air filter*. U S Patent 7,311,752.

Valegård, K., Liljas, L., Fridborg, K., & Unge, T. (1990). The three-dimensional structure of the bacterial virus MS2. *Nature*, 345, 36–41.

Wang, M., & Broni, G. (2007). The effect of RH on glass microfiber filtration efficiency for airborne bacteria and bacteriophage over time. *Aerosol Science and Technology*, 41, 775–785.

Yang, S., Lee, W. M. G., Huang, H. L., Huang, Y. C., Luo, C. H., Wu, C. C., et al. (2007). Aerosol penetration properties of an electret filter with submicron aerosols with various operating factors. *Journal of Environmental Science and Health Part A—Toxic/Hazardous Substances & Environmental Engineering*, 42, 51–57.

Yun, K. M., Hogan, C. J., Jr., Matsubayashi, Y., Kawabe, M., Iskandar, F., & Okuyama, K. (2007). Nanoparticle filtration by electrospun polymer fibers. *Chemical Engineering Science*, 62, 4751–4759.

Zhu, B., Clifford, D. A., & Chellam, S. (2005). Virus removal by iron coagulation–microfiltration. *Water Research*, 39, 5153–5161.