ISSN 1738-8716(Print)
ISSN 2287-8130(Online)
Particle and Aerosol Research
Part. Aerosol Res. Vol. 12, No. 3: September 2016 pp. 73-80
http://dx.doi.org/10.11629/jpaar.2016.9.30.073

필터와 이온을 이용한 공기살균법 연구동향

우 창 규·김 학 준·김 용 진·한 방 우[1)]
[1)]한국기계연구원 환경에너지기계연구본부 환경기계시스템연구실
(2016년 6월 16일 투고, 2016년 8월 19일 수정, 2016년 9월 30일 게재확정)

Air sterilization using filter and air ions: A review

Chang Gyu Woo, Hak-Joon Kim, Yong-Jin Kim, Bangwoo Han[1)]
[1)]*Department of Eco-Machinery Systems, Environmental and Energy Systems Research Division, Korea Institute of Machinery & Materials*

Abstract

Bioaerosol inactivation becomes important as people recognize the significance on the health effects of bioaerosols. There are several ways to inactivate such bioaerosols such as antimicrobial filters, UV, etc. For the on-filter-inactivation, proper antimicrobial materials coating should be applied. Recently, air ions are adopted to effectively reduce germ and virus activity. Limitations arise when each method is applied separately. Coating materials can experience chemical instability over time and temperature. Ionizers can generate ozone to prepare high ion concentrations. Combinations of developed techniques to enhance the inactivation efficiency were suggested. Researches on the air sterilization are reviewed and outlook is highlighted. Proper techniques such as combinations of filter material coating and air ion generation can be used to make air quality better for human living.

Keywords : air quality, filter, ion, antimicrobial, inactivation

* Corresponding author.
Tel : +82-42-868-7068
E-mail : bhan@kimm.re.kr

1. Introduction

The air quality is attracting people's concern due to high concentration of fine dust in the Korean peninsula atmosphere and recent events such as the outbreak of MERS (Middle-East Respiratory Syndrome) (Cowling et al. 2015) and over two hundred deaths for using improper chemicals in the several humidifier sterilizers in 2011 (Kim et al. 2013). Bioaerosols includes bacteria, virus, fungi and pollen which are biogenic. They can cause allergic symptoms, acute toxic effect and transmissible disease (Douwes et al. 2003). Once they become aerosol form, they can travel through the air. Filters are used most widely for indoor air. For crowded area, cost for air filtering increases because air capacity to handle is much higher. Some bioaerosols such as bacteria, viruses and fungi can grow on the filter surface. The probability that they can emit bioaerosols through the filter increases without proper management. To lower the burden the management, many sterilization methods were applied so far. Such air sterilizing techniques will be discussed here.

2. On-filter-inactivation technique

Reducing bioaerosol concentrations in the air by using filters make bioaerosol concentrations high on filters. One of the inactivating them on the filter surface is antimicrobial coating. Inorganic materials such as silver nitrate ($AgNO_3$) (Miaśkiewicz-Peska and Łebkowska 2011), silver nanoparticles (Joe and Hwang 2013; Joe et al. 2016) are known to inactivate bacteria on the filter surface. Miaśkiewicz-Peska et al. tried hydrophobic polypropylene filters with silver nitrate, potassium jodate and hydrated sodium tetraborate for five bacterial strains (*Micrococcus luteus, M. roseus, Bacillus subtilis, Pseudomonas luteola and P. putida*). Silver nitrate showed effective on bacteria inactivation. For silver nitrate coating on the filter surface, 2 % silver nitrate in the ethanol solution poured to the filter surface and dried. Pressure drop was measured before the coating process only, not after the process. This may change the pressure drop and filter characteristics (Liew and Conder 1985). The silver nitrate concentration of surrounding air to find emission of silver nitrate to the air was measured. They did not stated the emission level of 0.00034 mg/(l·h) would be dangerous or not.

Joe et al. (2016, 2013) showed silver nanoparticles which is generated by spark discharge method can effectively reduce activity of bacteria and virus on filter. *Escherichia coli* and *Staphylococcus epidermidis* were used as test bacteria, bacteriophage MS2 virus was used as test virus. As the amount of dust increases on the filter, the inactivation efficiency decreased.

Silver particles are prepared through electroless deposition method onto activated carbon fiber filters (Yoon et al. 2008). *E. coli* and *B. subtilis* are inactivated within 60 minutes. An ACF filter which has gas adsorption ability was chosen because bacteria can survive on carbon surfaces compared to other surfaces. To suppress silver nanoparticle agglomeration, silica nanoparticle templates were prepared (Ko et al. 2014). Unagglomerated particles showed higher inactivation rate. Those raspberry-like nanoparticles are delivered to the glass fiber filter, and showed antimicrobial activity against *E. coli* and *S. epidermidis*. Silver nanoparticles and multiwalled carbon nanotubes (MWCNT) are prepared to deposit on polyurethane (PU) resin fiber filter to suppress *E. coli* and *S. epidermidis* activity (Jung et al. 2011a). Combination of silver and MWCNTs showed higher inactivation ability than other cases.

ZnO nanorods are applied to the ePTFE filter surface (Zhong et al. 2015). Atomic layer deposition (ALD) and hydrothermal reaction could successfully build ZnO nanorod structure on filter. Like other methods, as deposition amount increases, pressure drop increased. Capture efficiency of filter increased over 99.99% and inactivation rates on *E. coli* and *S. aureus* were over 99% compared to pristine filter of capture efficiency of 96% and inactivation rate of 0%.

Filter coating has chance to emit coated material after the filter even though the amount is little. Those particulate matters can have negative effect on human health. Incorporating antimicrobial materials into the filter fiber during filter fabrication process can reduce the effluent problem. However, those processes can reduce the antimicrobial efficiency. Natural antimicrobial product may circumvent the danger. Natural product indicates that material from natural resources such as trees and vegetables which usually contain polyphenolic material by extraction process. Low dose of natural product may be less harmful than synthetic material.

Natural products such as *Sophora flavescens* extract coating on PU resin filter can effectively applied as in Jung et al.(2011)'s work. Major components of S. flavescens are kurarinone, kuraridin, and sophoraflavanone G (Sim et al. 2014). As they increased the amount of *S. flavescens* nanoparticles on the filter, pressure drop across the filter increased and antimicrobial activity increased. Gram-negative *E. coli* showed higher resistance to antimicrobial than *S. epidermidis* and *B. subtilis*. The inactivation efficiency can be increased by using electrospray coating method (Jung et al. 2013) not by using nebulization by making antimicrobial particle smaller in size for enlarging the contact area.

Table 1. On-filter-inactivation method

Inactivation method		Target strain	Filter material	Reference
Inorganic material coating on filter	$AgNO_3$	*M. luteus, M. roseus, B. subtilis, P. luteola, P. putida*	PP	Miaśkiewicz-Peska and Łebkowska 2011
	AgNP	*E. coli, S. epidermidis,*	Glass fiber	Joe and Hwang 2013
		E. coli, B. subtilis	ACF	Yoon et al. 2008
		bacteriophage MS2	Glass fiber	Joe et al. 2016
	AgNP@SiO_2	*E. coli, S. epidermidis*	Glass fiber	Ko et al. 2014
	Ag/MWCNT	*E. coli, S. epidermidis*	PU resin fiber	Jung et al. 2011a
	ZnO nanorod	*E. coli, S. aureus*	ePTFE	Zhong et al. 2015
Organic material coating on filter	*S. flavescens* extract	*S. epidermidis, B. subtilis, E. coli*	PU resin fiber	Jung et al. 2013; Hwang et al. 2012; Chong et al. 2013; Jung et al. 2011b
	E. japonica extract	*S. epidermidis, M. luteus*	PU resin fiber	Hwang et al. 2015a
	GSE, propolis	*S. aureus*	PET	Woo et al. 2015
	GSE, propolis, shiitake extract	*S. aureus, M. luteus, P. aeruginosa, E. coli*	PET	Han et al. 2015
	Tea tree, eucalyptus oil	Influenza A	PP	Pyankov et al. 2012
Combination of organic/inorganic material	CNT, *S. flavescens*	*S. epidermidis*	PU resin fiber	Hwang et al. 2015b
	S. flavescens extract, electrets on filter	*S. epidermidis*	PU fiber	Sim et al. 2015

However, their stability can be decreased by humid air exposure (Hwang et al. 2012) and chemical instability by time appeared over 90 days (Chong et al. 2013). *E. japonica* extract applied to the PU filter and showed similar behavior (Hwang et al. 2015a).

Grapefruit seed extract (GSE) (Han et al. 2015; Woo et al. 2015), propolis (Han et al. 2015), shiitake extract (Han et al. 2015) on polyethylene terephthalate (PET) filter are used for inactivating *S. aureus* and other strains. The major component of GSE is ascorbic acid, naringin and other flavonoids. Tea tree and eucalyptus oils (Pyankov et al. 2012) are used for influenza A virus on polypropylene fiber filter. Tea tree oil has terpinen-4-ol and 1,8-cineole and eucalyptus oil has 1,8-cineole, a-pinene and a-terpineol. Those components from natural product extracts can play a role for antimicrobial ability for air filters.

Combinations of organic and inorganic antimicrobial material on filter coating were tried by Hwang et al. (2015b). They used twin-head electrospray system (THES) to assemble MWCNT particles and S. *flavescens* particles. Coulombic forces are applied to the oppositely-charged particle and those assembled particles are deposited on PU resin fiber filter. A *S. epidermidis* strain was tested. The MWCNT has bigger effect on pressure drop than *S. flavescens*. Synergistic effect arouse when the hybrid filter was used for inactivating bacteria. Ion implantation on polymer filter surface with corona discharge can be combined with *S. flavescens* extract (Sim et al. 2015). Electrostatic forces on the filter increased *S. flavescens* coating efficiency over 10% based on number concentration where geometric mean diameter of generated *S. flavescens* particle was 139.4 nm. The filtration efficiency of KCl particle which is assumed to be dust particles was increased after electrification, as well as *S. epidermidis* particles. Attached ion on the filter surface can be used to increase filter performance.

Table 1 shows the summary of on-filter inactivation method described above. Papers regarding silver nanoparticles and other combination are reported and natural products are used to air filters. Most filters were polymeric fiber filters and *E. coli* and *S. epidermidis* are frequently used.

3. Off-filter-inactivation technique

Unlike filter coating, air ions can be adopted to inactivate bacteria activity (Kim et al. 2011). Ions irritate cell membranes and induce cell death (Noyce and Hughes 2003; 2002; Mendis et al. 2000).

Park et al. (2009) generated positive air ion by applying high voltage on carbon fibers which is c. a. 7 mm in diameter. *E. coli* inactivation rate was increased as ion concentration increases and the exposure time increases. Negative air ions are generated inside closed acryl chamber and bacteria *Pseudomonas flurorescens* was exposed to the ion on the petri dish in the chamber (Tyagi et al. 2008). They investigated the effect of media, concentration of ion and exposure time. They prepared starvation situation for the bacteria, and the starvation made cells more resistant to the ion. Culture age was also investigated and younger phase bacteria was more resistant compared to other phase. Lee et al.(2014) described alternating polarity configuration of ionizers for inactivating bioaerosol of *S. epidermidis*. Increasing numbers of ionizers of the same polarity did not showed distinct difference. However, changing polarity downstream has higher inactivation rate with increasing number of changes.

UV irradiation inside the steel cyclone chamber was done to inactivate *S. aureus, P. aeruginosa*, and *Legionella pneumophila*. Ultraviolet germicidal irradiation (UVGI) is a well-known technique to suppress bioaerosol proliferation in the indoor air. Steel cyclone is thought to be to avoid degradation. By changing flowrate and relative humidity, the inactivation rate was analyzed. High humid environment showed low inactivation efficiency when UV is irradiated. TiO_2 coated filter was prepared to capture bioaerosols and to inactivate them by Pigeot-Remy et al.(2014). Photocatalytic reaction can take place on TiO_2 surface with UV irradiation. Commercial TiO_2 powder was coated with inorganic binder. *E. coli* aerosols are generated by nebulizer. UV-A and UV-C was irradiated to the filter surface. The UV spectra were controlled by cut-off filter. The shorter wavelength of UV-C was more effective than UV-A on inactivating *E. coli*.

Atmospheric pressure non-thermal plasma was applied to the air directly (Liang et al. 2012). 14 kV with a 10 kHz was applied to the air (24W) to suppress *P. fluorescens* and B. subtilis. Those bioaerosols are inactivated within milliseconds.

For higher inactivation, ion and natural product was combined. Essential oil vapors and negative air ions in particular have been used (Tyagi and Malik 2012; Tyagi and Malik 2010), the combination of which achieved direct inactivation of floating microorganisms. Candle flame was used to generate ions by Gaunt et al.(2005). They used candle-generated ion and -pinene and orange oil which is contained to the candle to *E.*

Table 2. Off-filter-inactivation method

Inactivation method		Concentration (ions/m^3)	Target strain	Filter material	Duct material	Reference
Unipolar ion (positive)		~1.3×10^{13}	*E. coli*	Glass fiber	acryl	Park et al. 2009
Unipolar ion (negative)		~2×10^{12}	*E. coli, P. fluorescens*	-	acryl	Tyagi et al. 2008
Unipolar and bipolar ion		~4.0×10^{13}	*S. epidermidis*	-	acryl	Lee et al. 2014
UV irradiation		-	*S. aureus, P. aeruginosa, Legionella pneumophila*	-	steel	Chang et al., 2013
UV irradiation on photocatalytic filter		-	*E. coli*	cellulose, polyester fiber filter with TiO_2, glass fiber and acrylic latex with TiO_2	glass	Pigeot-Remy et al., 2014
Atmospheric pressure non-thermal plasma		-	*B. subtilis, P. fluorescens*	-	-	Liang et al. 2012
Combination with other method	Lemon grass oil vapor	~1×10^{12}	*E. coli*	-	acryl	Tyagi and Malik 2012
	Essential oil vapor	~2×10^{12}	*P. fluorescens*	-	acryl	Tyagi and Malik 2010
		~10^{11}	*E. coli, S. aureus*	-	acryl	Gaunt et al. 2005
	Mukdenia rossii (Oliv) Koidz	~7.6×10^{11}	*S. epidermidis*	polymer	-	Lee et al. 2013

coli and *S. aureus* in a closed acryl chamber. Natural product, *Mukdenia rossi (Oliv) Koidz* and ions from ionizer was applied to the commercial face mask which is made of polymer (not described). Ion emission increased inactivation rate by 20~25%.

Table 2 shows the summary of off-filter-inactivation methods. Using ion can enhance antimicrobial activity of filter. When it is combined to other method such as antimicrobial material coating on filter, antimicrobial efficiency can increase. Most frequent filter duct material was acryl. Especially for ion, wall loss would be increased at the surface. When the material is grounded metal surface, ion loss will be greater near the ionizer. One of the way to increase the ion concentration is using electrically-grounded filter (Woo et al., submitted)

4. Conclusion

We reviewed recent research on indoor air sterilization with filter. Antimicrobial material coating is direct and immediate method to inactivate microbe which is captured on the filter. Antimicrobial action takes on the contact surface, this coating method is efficient. There are possibilities to emit coated material and to get to be instable over time. The off-filter-inactivation method such as ion supplying on filter can be an alternative as long as they do not generate ozone. However, they may have limits on filter and surrounding material. Combination of on and off-filter-inactivation technique is promising. It is cost effective and durability would be much higher.

Acknowledgement

This research was primarily supported by the Eco-Innovation Project operated by the Korea Ministry of the Environment, and partially by a General Research Fund (NK197B) from the Korea Institute of Machinery and Materials.

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