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Effectiveness of Photocatalytic Techniques for Disinfection of Indoor Bioaerosols

Seoung-Ho Shin*, Mo-Geun Kim and Wan-Kuen Jo***

*Department of Environmental Engineering, Kyungpook National University, Daegu 702-702, Korea
**National Environment and Health Research Institute of Kyungpook Province, Daegu, 702-702, Korea
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The current study evaluated the technical feasibility of the application of titanium dioxide (TiO_2) photocatalytic air cleaners for the disinfection of bioaerosols present in indoor air. The evaluation included both laboratory and field tests and the tests of hydraulic diameter (HD) and lamp type (LT). Disinfection efficiency of photocatalytic oxidation (PCO) technique was estimated by survival ratio of bacteria or fungi calculated from the number of viable cells which form colonies on the nutrient agar plates. It was suggested that the reactor coating with TiO_2 did not enhance the adsorption of bioaerosols, and that the UV irradiation has certain extent of disinfection efficiency. The disinfection efficiency increased as HD decreased, most likely due to the decrease in the light intensity since the distance of the catalyst from the light source increased when increasing the HD. It was further suggested that the mass transfer effects were not as important as the light intensity effects on the PCO disinfection efficiency of bioaerosols. Germicidal lamp was superior to the black lamp for the disinfection of airborne bacteria and fungi, which is supported by the finding that the disinfection efficiencies were higher when the germicidal lamp was used compared to the black lamp in the laboratory test. These findings, combined with operational attributes such as a low pressure drop across the reactor and ambient temperature operation, can make the PCO reactor a possible tool in the effort to improve indoor bioaerosol levels.

Key Words : Bacteria, Fungi, Hydraulic diameter, Lamp type; Titanium dioxide

1. Introduction

Exposure to microbial aerosols (bioaerosols) has become a public concern because of the prevalence in environments and the related adverse health effects. Owing to their ubiquitous presence in nature, the presence of bioaerosols is inevitable in many microenvironments including indoor air[1~3]. The last decade has been characterized by a significant increase in the scientific database on environmental exposure to bioaerosols in many countries for the purpose of evaluating the relationship between exposure and health effects[2]. Consequently, certain investigations have reported that exposure to large concentrations of airborne microbes is often associated with asthma and rhinitis[4], hypersensitivity pneumonitis[5], sick-building syndrome[6], and a number of other health effects, including infections[7].

The prevalence of bioaerosols in indoor air and their potential health effects warrant the development of control strategies for indoor bioarosols. Several recent researches have been performed to suggest that a photocatalytic system can destroy environmental microorganisms, and possible disinfection mechanisms have been postulated[8~12]. However, much less information on such photocatalytic disinfection (PCD) of air is currently available, whereas many previous studies have dealt primarily with PCD of water[13]. A possible mechanism for air disinfection which was suggested by Jacoby et al.[14] includes the following sequential pathway: (i) bulk mass transport of the bioaerosols from the gas phase to the surface of the catalyst and immobilization on the catalyst surface; (ii) kill of bioaerosols on the catalyst surface; and (iii) oxidation of bioaerosols. In particular, Jacoby et al.[14] surveyed the last pathway, oxidative decomposition of cell mass and reported the evidence for the catalytic oxidation of whole cells to carbon dioxide, suggesting

Corresponding Author : Wan-Kuen Jo, Department of Environmental Engineering, Kyungpook National University, Daegu 702-702, Korea
Phone: +82-53-950-6584
E-mail: wkjo@knu.ac.kr

that a photocatalytic surface used for disinfection can be self-cleaning in a heterogeneous system (air-solid). This suggestion precludes a hypothesis that the dead or damaged microbial cells have a potential to accumulate and block the active photocatalyst surface.

The current study evaluated the technical feasibility of the application of TiO_2 photocatalytic air cleaners for the disinfection of bioaerosols present in indoor air. The evaluation included both laboratory and field tests and the tests of hydraulic diameter (HD) and lamp type (LT). The effect of HD on photocatalytic oxidation (PCO) destruction efficiency was tested since UV intensity on the reactor surface is an important parameter[15] and varies with the HD of the PCO reactor for an identical UV lamp. Here, HD is defined as the inside diameter of the annular reactor tube minus the outside diameter of the lamp. In addition, LT (germicidal and fluorescent lamps typically employed for the PCO system) is expected to be an important parameter for the air disinfection[16].

2. Experimental

2.1. Experimental Protocol

A schematic of the experimental system is presented in Fig. 1. The PCO reactors used in this investigation had annular geometries. The reactor consisted of a *Pyrex* tube coated on the inner surface with a thin film of the TiO_2 photocatalyst (20% Degussa P-25 slurry). The coated reactor is dried for an hour at room temperature and baked for 30 min at 450 °C. A cylindrical UV light source was inserted inside the *Pyrex* tube and served as the inner surface of the reactor. The air flowed through the annular region. This design is particularly suited for research, because it provides a well-characterized reactive catalyst surface along the length of the reactor body and allows uniform light distribution[14,16]. Moreover, the reactor was designed to direct the flow of incoming air toward the UV light in order to increase the air turbulence inside the reactor, thereby enhancing the distribution of air onto the catalytic surface of the reactor. This type of PCO reactor has been successfully employed to efficiently remove several volatile organic compounds associated with indoor environmental issues[17].

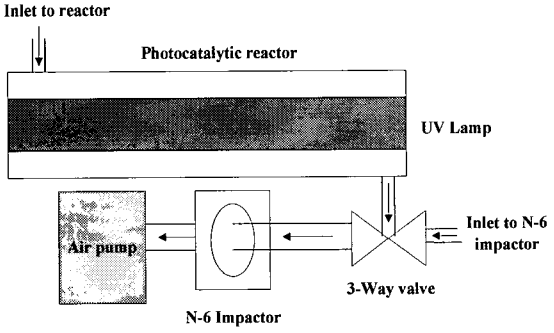

Fig. 1. Schematic diagram of the experimental set-up for PCO disinfection efficiency tests of bioaerosols.

The present study was conducted in two different indoor environments: a university laboratory and an indoor flower garden. These two environments were selected to maximize the concentration range of bioaerosols at inlet of the PCO[18]. For the laboratory experiment, two parameters (HD and LT) were tested for the PCO efficiencies of bioaerosol disinfection under four reactor conditions (an uncoated (no titania) reactor with turning UV lamp off, an uncoated reactor with turning UV lamp on, TiO_2-coated reactor with UV lamp off, and TiO_2-coated reactor with UV lamp on). Based on the laboratory experiment, the field experiment was conducted under two reactor conditions only (TiO_2-coated reactor with UV lamp off and TiO_2-coated reactor with UV lamp on). Three HDs (5.0, 20, and 45 mm) were tested using two lamps (germicidal and fluorescent lamps. The UV radiation is supplied by an 4-W germicidal lamp (SANKYO DENKI, F40T8GL) or an 8-W fluorescent black light (SANKYO DENKI F8T5/BLB) with a maximum spectral intensity at 352 nm. New bulbs were used for every test to minimize any confounding factors that might influence the test results due to different bulb ages. The weight of TiO_2 coating was fixed to 0.5 mg/cm^2. For each parameter test, all of the other parameters were all fixed at representative values. The laboratory test focuses on total bacteria and total fungi, while the flower garden test focuses on four major fungal species (*Aspergillus*, *Alternaria*, *Cladosporium*, and *Penicillium*) as well as total bacteria and total fungi. Contrast to the total bacterial and total fungal tests which examined two parameters (HD and LT) for disinfection efficiency, the fungal species tests were conducted to examine the LT effects only, by fixing HD to 20 mm. Laboratory or flower garden indoor air stream was drawn to the PCO reactor, and

the bioaerosol samples were collected at the PCO reactor inlet prior to and outlet one hour after operating the PCO reactor. In addition, other samples were collected at the reactor inlet after the outlet sampling. The average of these two inlet concentrations was then used as the inlet bioaerosol concentrations in this paper. Ambient temperature and relative humidity were recorded prior to or right after the bioaerosol sampling. In an individual test, the air flow level was set to 28.3 l/min, corresponding to the bioaerosol sampling flow rate. All individual experiments were repeated five times.

2.2. Sampling and Analysis

Viable bioaerosol sampling was conducted using single-stage Anderson samplers with four holes (0.25 - mm OD) at a flow rate of 28.3 l/min[3]. Samplers were calibrated prior to and following the collection of each sample with a flow calibrator (DCL-H, Bios, Butler, NJ). The average of these two rates was then used as the sampling flow-rate for all the volume calculations. The residence time was calculated by dividing the the volume of the reactor by the volumetric flow rate. No samples departed more than 10% from the initial flow rate during the study. During sampling, the temperature and relative humidity were recorded.

Each bioaerosol sample was nominally collected for 0.5 min for the flower garden samples and 2 min for the laboratory samples, following Nevalainen et al.[19], on nutrient media (specific to either fungi or bacteria) in Petri-dishes located on the impactor. Dichloran glycerol 18 agar (DG-18) was applied for fungi, with chloramphenicol added to inhibit baterial growth. Tryptic soy agar (TSA) was used for bacteria, with cycloheximide added to inhibit fungal growth. The DG-18 and TSA plates were incubated at room temperature for 3 to 5 days and 5 to 7, respectively. The counts for the air sample plates were corrected for multiple impactions using the positive hole conversion method, and reported as colony forming units per cubic meter of air (CFU/m^3). The genera of certain cultures of fungi were identified based on their micro and macromorphological characteristics, using standard taxonomic keys[20].

3. Results and Discussion

3.1. Effects of HD on Bioaerosol Disinfection

Three reactors with different HDs (5, 20, and 45 mm) were tested as regards the PCO efficiencies for bioaerosols. Table 1 displays the removal efficiencies for bacteria obtained from a university laboratory. Regardless of HDs, the disinfection efficiencies obtained using both the uncoated reactor with turning UV lamp off and the coated reactor with turning off were similar each other, suggesting that the reactor coating with TiO_2 did not enhance the adsorption of bioaerosols. However, the removal efficiencies obtained using the uncoated reactor with turning UV lamp on were higher than those for the uncoated reactor with turning UV lamp off. Similarly, the removal efficiencies obtained using the TiO_2-coated reactor with turning UV lamp on were higher than those for the coated reactor with turning UV lamp off. Hence, it is suggested that the UV irradiation has certain extent of disinfection efficiency. This assertion is supported by previous reports, in that UV radiation was effective for inactivating airborne microorganisms[21~23].

For the TiO_2-coated 5.0-mm-HD reactor with turning UV lamp the bacterial disinfection efficiencies

Table 1. Removal efficiency (%) of airborne bacteria in a university laboratory for four reactor conditions according to HDs and LTs[a]

LTs[b]	5 mm				20 mm				45 mm			
	UCOFF	UCON	COFF	CON	UCOFF	UCON	COFF	CON	UCOFF	UCON	COFF	CON
Black	23.2	40.9	24.2	47.3	22.4	35.2	21.8	42.1	22.8	30.4	23.6	34.1
Germ	21.7	45.7	23.4	55.2	21.3	40.3	22.5	40.4	20.4	34.8	22.5	33.9

[a] Reactor conditions: UCOFF, an uncoated reactor with turning UV lamp off; UCON, a uncoated reactor with turning UV lamp on; COFF, TiO_2-coated reactor with UV lamp off; and CON, TiO_2-coated reactor with UV lamp on. The number of data for each reactor condition is 5. Average inlet concentration of bacteria was 255 CFU/m^3.

[b] LTs: black, 8-W fluorescent black light; and germ, 4-W germicidal lamp.

Table 2. Removal efficiency (%) of airborne fungi in a university laboratory for four reactor conditions according to HDs and LTs[a]

LTs[b]	5 mm				20 mm				45 mm			
	UCOFF	UCON	COFF	CON	UCOFF	UCON	COFF	CON	UCOFF	UCON	COFF	CON
Black	22.9	55.6	30.1	67.1	21.6	46.6	23.3	47.4	20.2	43.1	21.8	44.6
Germ	23.3	67.5	31.4	75.6	21.1	54.3	22.9	56.7	18.7	48.5	20.3	47.3

[a] Reactor conditions: UCOFF, an uncoated reactor with turning UV lamp off; UCON, a uncoated reactor with turning UV lamp on; COFF, TiO_2-coated reactor with UV lamp off; and CON, TiO_2-coated reactor with UV lamp on. The number of data for each reactor condition is 5. Average inlet concentration of fungi was 272 CFU/m^3.
[b] LTs: black, 8-W fluorescent black light; and germ, 4-W germicidal lamp.

(47.3% and 55.2% for black lamp and germicidal lamp, respectively) were higher than those for the coated 20-mm-HD reactor (42.1% and 40.4% for black lamp and germicidal lamp, respectively), which in turn were higher than those for the coated 45-mm-HD reactor (34.1% and 33.9% for black lamp and germicidal lamp, respectively). As shown in Table 2, fungi exhibited similar trends to bacteria for the disinfection efficiencies according to the reactor diameters. Moreover, in the field studies the removal efficiency decreased as the HD increased: in Table 3, in a flower garden, the bacterial disinfection efficiencies by the 5.0-mm HD reactor were 55.5% and 66.3% for black lamp and germicidal lamp, respectively; those by 20-mm, 43.7% and 49.1%; those by 45-mm, 38.%8 and 45.4%. Similarly, the fungal disinfection by the 5.0-mm HD reactor were 79.2% and 86.8% for black lamp and germicidal lamp, respectively; those by 20-mmm, 56.6% and 64.3%; those by 45-mm, 53.4% and 60.54% (Table 4). As such, it is suggested that the HD of the PCO reactor is an important parameter. when applying TiO_2 photocatalytic technology to the removal of indoor bioaerosols. As the distance of the catalyst from the light source increases when increasing the HD, the decrease in the light intensity seems to be the most obvious reason for the drop in the PCO of the VOCs. The UV radiation intensities measured in the current study were 5.8 and 3.8 mW/cm^2 for the 5.0- and 20-mm HDs, respectively. The effect of the UV radiation intensity is also supported by Obee and Brown's study[24], which found that the oxidation rate of certain chemicals, instead of bioaerosols, increased with an increase in the UV intensity. In the present study, the flow rate was increased with the larger reactor volume to give the same residence time.

Table 3. Removal efficiency (%) of airborne bacteria in a flower garden for four reactor conditions according to HDs and LTs[a]

LTs[b]	5 mm		20 mm		45 mm	
	COFF	CON	COFF	CON	COFF	CON
Black	28.7	55.5	26.4	43.7	24.3	38.8
Germ	27.3	66.3	24.9	49.1	25.1	45.4

[a] Reactor conditions: COFF, TiO_2-coated reactor with UV lamp off and CON, TiO_2-coated reactor with UV lamp on. The number of data for each reactor condition is 5. Average inlet concentration of bacteria was 3550 CFU/m^3.
[b] LTs: black, 8-W fluorescent black light; and germ, 4-W germicidal lamp.

Table 4. removal efficiency (%) of airborne fungi in a flower garden according for four reactor conditions according to HDs and LTs[a]

LTs[b]	5 mm		20 mm		45 mm	
	COFF	CON	COFF	CON	COFF	CON
Black	29.2	79.2	36.5	56.6	25.5	53.4
Germ	28.6	86.8	36.9	64.3	25.7	60.5

[a] Reactor conditions: COFF, TiO_2-coated reactor with UV lamp off and CON, TiO_2-coated reactor with UV lamp on. The number of data for each reactor condition is 5. Average inlet concentration of fungi was 2284 CFU/m^3.
[b] LTs: black, 8-W fluorescent black light; and germ, 4-W germicidal lamp.

Therefore, the mass transfer also increased with the larger HD. However, the current results show that the mass transfer effects were not as important as the light intensity effects on the PCO disinfection efficiency of bioaerosols.

3.2. Effects of LT on Bioaerosol Disinfection

Regardless of the HDs, in most cases, the dis-

Table 5. Removal efficiency (%) of four airborne fungal species in a flower garden for four reactor conditions according to HDs and LTs[a]

Fungal species	LTs[b]	5 mm		20 mm		45 mm	
		COFF	CON	COFF	CON	COFF	CON
Aspergillus	Black	32.3	78.4	31.7	61.4	25.4	50.7
	Germ	31.5	89.2	33.5	70.1	23.7	57.3
Alternaria	Black	28.3	81.7	37.3	63.2	21.5	53.5
	Germ	29.8	86.5	35.4	69.4	24.3	59.9
Cladosporium	Black	27.6	82.5	36.0	71.1	27.2	52.7
	Germ	25.4	88.3	43.3	88.6	26.8	61.1
Penicillium	Black	26.4	75.6	40.2	73.7	27.1	55.4
	Germ	25.9	84.5	38.5	80.2	29.2	60.9

[a] Reactor conditions: COFF, TiO_2-coated reactor with UV lamp off and CON, TiO_2-coated reactor with UV lamp on. HD was fixed to 0.5 mm and WT to 0.5 mg/cm^2. The number of data for each reactor condition is 5.

[b] LTs: black, 8-W fluorescent black light; and germ, 4-W germicidal lamp.

infection efficiencies were higher when the germicidal lamp (a maximum intensity at 254 nm) was used compared to the black lamp (a maximum intensity at 356 nm) in the laboratory test. Just a few cases exhibited similar results for the two lamps. As shown in Table 1, for the TiO_2-coated reactors with turning the germicidal lamp on the bacterial disinfection efficiencies obtained from the laboratory test were between 33.9% and 45.7%, whereas for the TiO_2-coated reactors with turning the black lamp on they were between 34.1% and 40.9%. For the TiO_2-coated reactors with turning the germicidal lamp on the fungal disinfection efficiencies obtained from the laboratory test were between 47.3% and 75.6%, whereas for the TiO_2-coated reactors with turning the black lamp on they were between 44.6% and 55.6% (Table 2). Similarly, in the flower-garden field test, the disinfection efficiencies were higher when the germicidal lamp was used compared to the black lamp (Tables 3 and 4). Moreover, the disinfection efficiencies for fungal species were similar to the bacterial or total fungal results(Table 5). The four most prevalent fungi (*Cladosporium*, *Penicillium*, *Aspergillus*, and *Alternaria*) detected in various microenvironments[25] have been strongly associated with allergic respiratory diseases such as asthma[26]. Accordingly, the use of the PCO technique can minimized health risks from inhalation exposure to these microorganisms. The difference in the disinfection efficiencies between the two lamp types are most likely due to stronger energy of the germicidal lamp due to the short wavelength emission. This assertion is supported by Stevens et al.[15], who reported that UV light intensity is an important parameter for destruction of chemicals, when a photocatayltic technique is employed. To our best knowledge, there were no published professional literatures associated with the cylindrical plug-flow type PCO reactors, although a batch-type reactor has been employed by Jacoby et al.[14]. Consequently, this kind of researches are recommended to confirm the present findings.

4. Conclusions

The current study evaluated the technical feasibility of the application of PCO-type air cleaners to the disinfection of bioaerosols present in indoor air. This evaluation included the tests of HD and LT. The disinfection efficiency increased as HD decreased, most likely due to the decrease in the light intensity since the distance of the catalyst from the light source increased when increasing the HD. It was further suggested that the mass transfer effects were not as important as the light intensity effects on the PCO disinfection efficiency of bioaerosols. Germicidal lamp would be superior to the black lamp for the disinfection of airborne bacteria and fungi, which is supported by the finding that the disinfection efficiencies in the laboratory test were higher when the germicidal lamp was used, as compared to the black lamp. These findings, combined with operational attributes such as a low pressure drop across the reactor and ambient temperature operation, can make the PCO reactor a

possible tool in an effort to improve indoor bioaerosol levels. However, since this kind of researche is very limited, further studies are recommended to apply the PCO technique to more efficient bioaerosol disinfection.

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