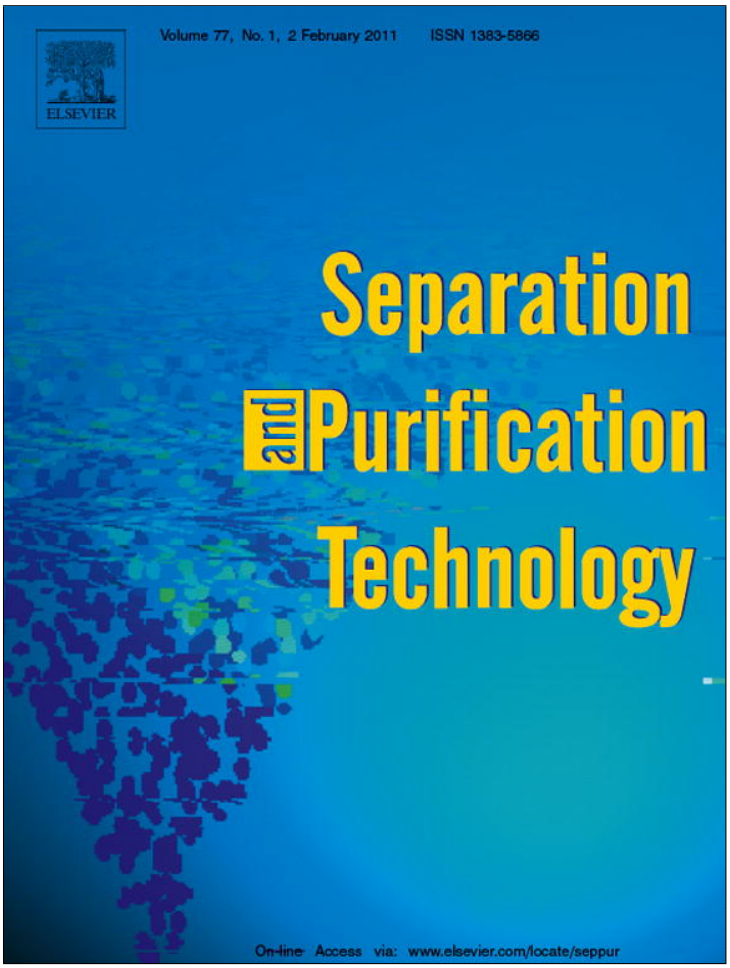

Separation and Purification Technology 77 (2011) 87–93

Contents lists available at ScienceDirect

Separation and Purification Technology

journal homepage: www.elsevier.com/locate/seppur

Simultaneous removal of odors, airborne particles, and bioaerosols in a municipal composting facility by dielectric barrier discharge

Chul Woo Park[a], Jeong Hoon Byeon[b], Ki Young Yoon[c], Jae Hong Park[a], Jungho Hwang[a,d,*]

[a] School of Mechanical Engineering, Yonsei University, Seoul 120-749, Republic of Korea
[b] LCD Division, Samsung Electronics Co., Ltd., Yongin 446-711, Republic of Korea
[c] Exhaust Emission Engineering Team, Hyundai Motor Company, Hwaseong 445-706, Republic of Korea
[d] Yonsei Center for Clean Technology, Yonsei University, Seoul 120-749, Republic of Korea

ARTICLE INFO

Article history:
Received 3 August 2010
Received in revised form
18 November 2010
Accepted 22 November 2010

Keywords:
Dielectric barrier discharge (DBD)
Municipal composting facility
Odors
Airborne particles
Bioaerosols

ABSTRACT

The process of waste decomposition releases odors, airborne particles, and bioaerosols; therefore, air quality control at composting facilities is very important to the health of workers and the effective operation of such facilities. Because dielectric barrier discharge (DBD) produces chemical species, it has been used to remove undesired species interesting for environmental applications. In this study, a DBD reactor was applied to a composting facility to simultaneously remove odors, airborne particles and bioaerosols. The power consumption required was below 18.9 W when the flow volume of the pollutant gas was 0.2 L and the concentrations of ammonia, amines, airborne particles, and bioaerosols were 150 (or 75) ppm, 140 ppm, 2.1×10^8 particles/m^3, and 1.1×10^4 CFU/m^3, respectively. The removal efficiency of contaminants in the air increased as the specific energy densities (SED) increased, with removal efficiencies of up to 80% and 76% being achieved for ammonia and amines. Moreover, the removal efficiency of the overall airborne particles was 75% when 113 J/L of SED was employed, while the bioaerosols removal efficiency was 89% when 38 J/L of SED used.

1. Introduction

The process of waste decomposition in composting facilities releases a variety of odors, airborne particles, and bioaerosols [1–6]. They cause infections or irritations to humans, especially to sensitive or sick people [2,4]. While some of the odors are not considered to cause health problems directly, they may well be associated with diseases and negative health effects, which may cause defensive reactions of people due to psychological effects [7]. For the reasons, adequate air quality control in composting facilities is very important to the health of workers and surrounding residents [8].

It is well known that dielectric barrier discharge (DBD) produces highly non-thermal plasma in a controllable way at atmospheric pressure and temperature [9]. DBD technologies have high decomposition efficiency and ability to be tuned by adjusting the power level to match the source flow, concentration and ozone generation, yet require no additional disposal [1]. Until recently, DBD has primarily been used as an effective ozone generator [10–12]. However, researchers are now investigating the feasibility of using DBD for a wide range of fields. Since DBD serves as a chemical reactor that produces active chemical species under various reactions, it has been used to remove various undesired species interesting for environmental applications.

The atmospheric destruction of odorous gases by DBD occurs via the direct collision of electrons with gas molecules. Also a small amount of ozone or nitrogen oxides are generated from air by the discharge, and these compounds then react with odorous gases [13–16]. To collect airborne particles, the particles are first charged in DBD, after which they are collected on DBD plates [17]. Generally, bioaerosols are sterilized by physical or chemical processes in the DBD reactor. The physical process proceeds by positive and negative ions in the discharge's streamer, while the chemical process is accomplished by ozone and atomic oxygen produced in the DBD [18].

Traditional odor control methods such as wet scrubbing, active carbon adsorption, ozone oxidation, and biofiltration are limitative technically and economically for the abatement of odor from industry facility. Non-thermal plasma techniques are typically characterized by high removal efficiency and relatively low power consumption [19,20]. Odors emitted from animal houses and wastewater treatment plants can be removed by plasma reactors such as a ferroelectric packed-bed plasma reactor [1] and a pulse corona reactor [15].

Compared to other non-thermal plasma reactors, DBD reactor has advantages of easy operation and high efficiency in generating

* Corresponding author at: School of Mechanical Engineering, Yonsei University, Seoul 120-749, Republic of Korea. Tel.: +82 2 2123 2821; fax: +82 2 312 2821.
E-mail address: hwangjh@yonsei.ac.kr (J. Hwang).

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doi:10.1016/j.seppur.2010.11.024

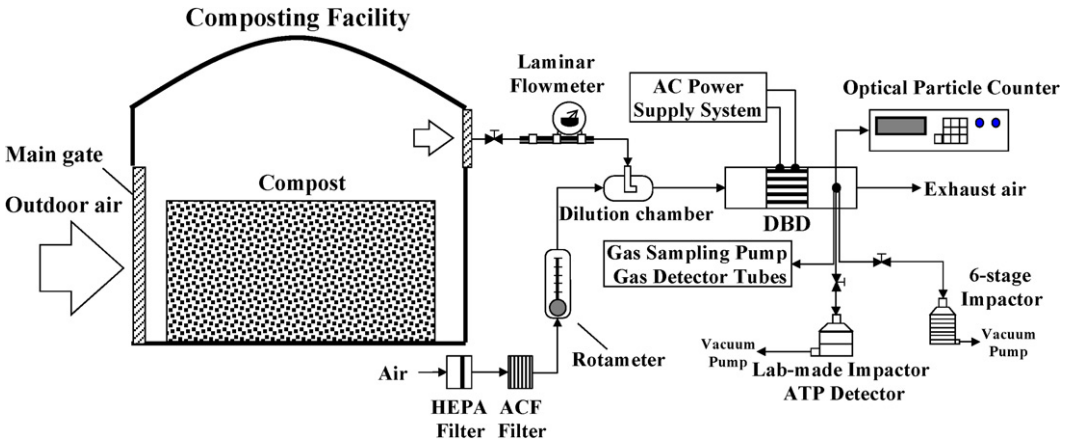

Fig. 1. Layout of the composting facility and experimental setup.

gas phase radicals [16]. Xia et al. [16] reported that in a DBD reactor ammonia was removed from gas streams within 0.1 s. Chen et al. [19,20] investigated the effects of humidity and balance gas mixture on energy yield and conversion efficiency of dimethyl sulfide and dimethylamine. Kim et al. [21] attempted to remove nitrogen oxide by a DBD reactor, and carried out numerical simulations to understand the observed streamer dynamics in the DBD reactor. Chang and Chang [22] performed a study on removing toluene and methyl ethyl ketone by a DBD reactor. In their study, the effects of gas temperature, O_2 content of gas, and water vapor content of gas on removal efficiency were reported, and simultaneous removal of toluene and methyl ethyl ketone was attempted. In Chang and Lee [23], the effectiveness of applying DBD plasmas for removal of formaldehyde was experimentally evaluated with a laboratory-scale apparatus. The removal efficiency of 97% was achieved with an applied voltage of 19 kV. Ye et al. [24] studied the destruction of gaseous benzene in both laboratory-scale and scale-up DBD reactors. Moreover, DBD technologies were recently evaluated to determine if they could be used for the collection of submicron particles and removal of gaseous contaminants. Byeon et al. [17] and Jidenko and Borra [25] attempted to remove submicron particles, and Kuroda et al. [26] investigated the simultaneous reduction of carbon particles and NO_x by DBD reactor. In addition, sterilization of *Escherichia coli* and *Fusarium oxysporum* with a DBD reactor was reported by Choi et al. [18] and Takayama et al. [27], respectively. However, a care is needed for using a DBD reactor, since the reactor can generate unwanted by-products such as ozone and nitrogen oxides [10,11,14], and produce high power peaks which may induce problems of electromagnetic hazards [28].

In our previous study [29], we studied the feasibility of the use of our lab-made DBD reactor in removing gaseous contaminants and airborne particles, separately. Toluene was selected as model gaseous contaminant, while a mixture of sodium chloride and dioctyl sebacate particles was selected as model airborne particles. In this study, we attempted to simultaneously remove odors, airborne particles, and bioaerosols from a municipal composting facility using a scale-up version of the lab-made DBD reactor. Ammonia and amines were selected as representative odor gases since strong ammonia and amines related odors are commonly produced during composting processes [30,31].

2. Materials and methods

Experiments were conducted at a full-scale composting facility in Dangjin-Gun, Korea, with a treatment capacity of 24 tons of food waste per day. The experimental schematic is shown in Fig. 1. The contaminated air emitted from the composting facility was diluted with particle-free and odor-free air that was delivered through a HEPA filter and an activated carbon fiber (ACF) filter. Next, the diluted mixture was treated by passing it through a DBD reactor at residence times of 0.35, 0.52, 0.69, 1, and 2.07 s. Under all test conditions, the gas temperature and humidity were approximately 25 °C and 55%, respectively.

The DBD reactor consisted of sixteen-parallel plate electrodes that were configured in an alternating fashion, with one electrode being grounded and the next one received high AC voltage. The gap spacing between any two electrodes was 5 mm. Each electrode was made of 0.03 mm thick copper foil (20 mm of streamwise length and 125 mm of spanwise length) sandwiched between two 0.3 mm thick dielectric plates (ceramic plates, 30 mm of streamwise length and 135 mm of spanwise length). Fig. 2(a) shows the voltage–current characteristics for frequencies of 60 and 120 Hz. Higher frequencies resulted in higher discharge current. The discharge currents were 0.2–1.7 and 0.2–2.25 mA for frequencies of 60 and 120 Hz, respectively. The power consumption was below 18.9 W when the flow volume of the pollutant gas was 0.2–L and the concentrations of ammonia, amines, airborne particles, and bioaerosols were 150 (or 75) ppm, 140 ppm, 2.1×10^8 particles/m^3, and 1.1×10^4 CFU/m^3, respectively. The voltage and current were measured using a two-channel digital oscilloscope (TDS 1012, Tektronix, USA) and their root-mean-square (RMS) amplitude values are indicated in Fig. 2(a). For these frequencies, the transition to arc occurred at voltages slightly higher than 9.5 kV. Fig. 2(b) shows the temporal voltage (rectangular) profile when the RMS voltage and frequency were 9 kV and 60 Hz, respectively. The DBD reactor was performed stably without thermal cracking of the electrodes.

The concentration of odorous gas was measured at a location downstream of the DBD reactor [31] using gas detector tubes. A gas sampling pump (GV-100S, Gastec Corporation, Japan) was used in conjunction with appropriate detector tubes, which changed color in response to the presence of odorous gas. The odorous gas removal efficiency (RE_{odor}) is defined by

$$RE_{odor} = 1 - \frac{C_{odor}}{C_{odor,0}} \quad (1)$$

where $C_{odor,0}$ is the initial gas concentration under each test condition when the power applied to the DBD reactor is turned off and C_{odor} is the concentration measured at a location downstream of the DBD reactor when the power applied to the DBD reactor is on.

The concentrations of airborne particles were measured at a location downstream of the DBD reactor using an optical particle counter (Portable Aerosol Spectrometer #1.109, Grimm Aerosol Technik GmbH & Co. KG, Germany) over 2 min (interval time: 6 s). The optical particle counter operates on the basis of optical light

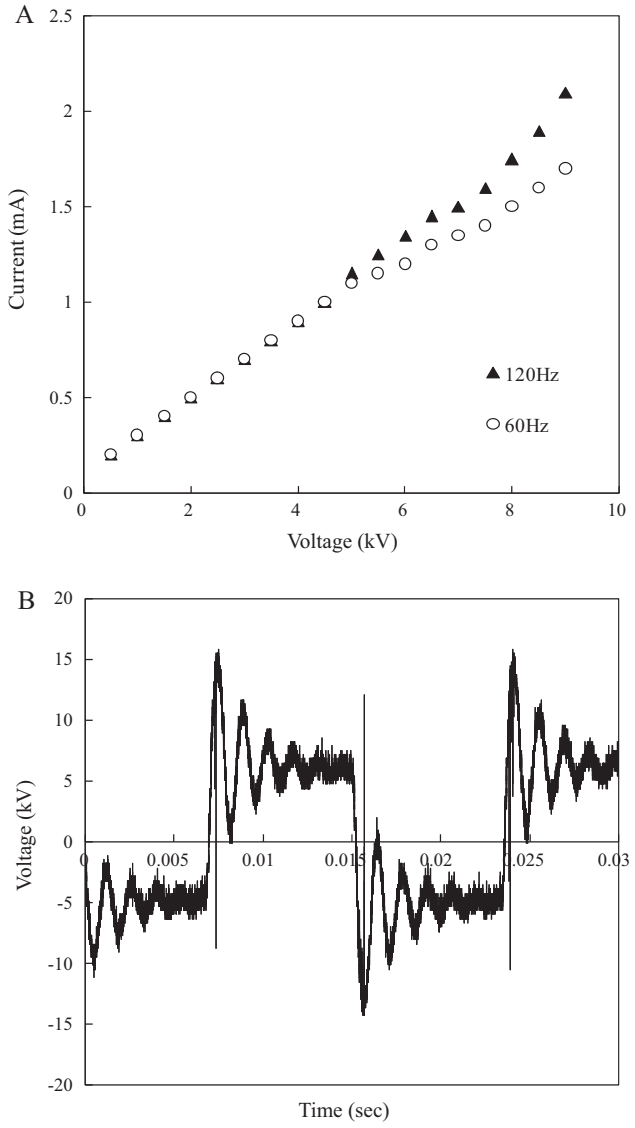

Fig. 2. (a) *I–V* characteristics of DBD reactor and (b) voltage profile (at 9 kV, 60 Hz).

scattering, which enables each single particle to be counted and its size determined. Specifically, the sample flow rate is fixed at 1.2 L/min and maintained by an internal flow controller. The air sample, which harbors differently sized particles, is constantly drawn through a flat beam of light generated by a focused laser diode via a volume-controlled pump. Each scattered signal generated by the disruption of this beam is then detected using a high-speed photodiode. The signals are then analyzed by an integrated pulse height analyzer, classified into one of 32 different size ranges and counted. The collection efficiency ($CE_{particle}(d_p)$) and overall collection efficiency ($CE_{particle,overall}$) of airborne particles of the DBD, excluding diffusional wall loss, are defined by

$$CE_{particle}(d_p) = 1 - \frac{C_{particle}(d_p)}{C_{particle,0}(d_p)} \quad (2)$$

$$CE_{particle,overall} = \frac{\int_0^\infty CE_{particle}(d_p) C_{particle,0}(d_p)\, dd_p}{\int_0^\infty C_{particle,0}(d_p)\, dd_p} \quad (3)$$

where $C_{particle,0}(d_p)$ is the particle number concentration of particles of size d_p when the power applied to the DBD reactor is turned off and $C_{particle}(d_p)$ is the concentration when the power to the DBD reactor is on.

To determine the biological removal efficiencies of airborne particles, we used a lab-made inertial impactor for sampling and a commercial portable adenosine 5′-triphosphate (ATP) detector that consisted of a swab stick (LuciPac W, Kikkoman, Japan) and a measuring instrument (Lumitester PD10-N, Kikkoman, Japan). A cut-off diameter of 1 μm was chosen for the impactor because this is the lowest size used in the U.S. Government Joint Biological Point Detection System [32]. Bioaerosols were sampled for 10 min by the impactor at a flow rate of 30 L/min. For every sampling event, the impaction plate was covered with new aluminum foil to prevent contamination. After sampling, the biological contaminants on the aluminum foil were measured using the ATP detector. To accomplish this, the surface of the aluminum foil was wetted with 0.1 mL of deionized water and then swabbed. The swab was then placed in a swab stick that contained ATP releasing reagent and luminescence reagent to produce a light generating reaction. The swab stick was then shaken several times and inserted into the measuring instrument, which reports the intensity of light generated from the reaction of ATP and luminescence reagent as relative luminescent units (RLU). The bioaerosols removal efficiency of the DBD ($RE_{bioaerosol}$) is defined by

$$RE_{bioaerosol} = 1 - \frac{RLU_{bioaerosol}}{RLU_{bioaerosol,0}} \quad (4)$$

where $RLU_{bioaerosol,0}$ is the RLU of bioaerosols when the power applied to DBD reactor is turned off and $RLU_{bioaerosol}$ is the RLU of bioaerosols when the power to the DBD reactor is on.

A six-stage impactor (TE-10-800, Tisch Environmental, USA) was used to collect microbiological samples, which were then evaluated by conventional culture-based methods [33]. Based on Górny et al. [34], Taha et al. [35] and Li et al. [36], impaction agar plates containing trypticase-soy agar (TSA), malt extract agar (MEA), and International *Streptomyces* Project medium 2 (ISP medium 2) were used to collect bacteria, fungi, and actinomycetes, respectively. The air was sampled by a vacuum pump at a constant flow rate of 28.3 L/min and the sampling times for bacteria, fungi and actinomycetes were 2, 4 and 4 min, respectively. Once the required air had been collected, the plates were sealed and incubated. The TSA plates were incubated at 30 °C for 5 days, while the MEA and ISP medium 2 were incubated for 7 days at 30 °C and 40 °C [4], respectively. After incubation, the number of colony forming units (CFU) was estimated by visual inspection.

The collected air samples were identified by the Korean Culture Center of Microorganisms. The bacterial isolates were gram-stained and then identified using the API kit (bio-Mérieux Co.) and the BIOLOG Microstation System. The isolates were stored as water suspensions at ambient temperature prior to use. Additionally, the cellular fatty acid compositions of the fungi and actinomycetes were analyzed via gas chromatography (GC, 6890 series, Agilent, USA). The retention time of each of the peaks was compared with that of the standard sample.

3. Results and discussion

Before performing experiment with our DBD reactor, we measured ammonia, amines, airborne particles, and bioaerosols which were emitted from the composting facility. Their average concentrations were 450 ppm, 400 ppm, 2.1×10^8 particles/m^3, and 1.1×10^4 CFU/m^3, respectively. Moreover, from the collected bioaerosol samples, 11 bacteria, 4 fungi, and 2 actinomycetes were isolated and identified (Table 1). Of the species identified in this study, *Staphylococcus lentus*, *Aspergillus fumigatus*, *Pseudallescheria boydii* and *Streptomyces rochei* have been identified in other municipal composting facilities [4].

Fig. 3 shows the dependence of gas removal efficiency on residence time when an applied voltage was 8.5 kV. The ini-

Table 1
Species of microorganisms in the sampled air.

Microorganism	Species identified
Bacteria	*Bacillus licheniformis*, *Bacillus subtilis*, *Brevibacterium* spp., *Burkholderia cepacia*, *Corynebacterium glucuronolyticum*, *Pasteurella pneumotropica*, *Ralstonia pickettii*, *Rhodococcus* spp., *Staphylococcus lentus*, *Virgibacillus pantothenticus*, *Weeksella virosa*
Fungi	*Aspergillus fumigatus*, *Aspergillus niger*, *Pithomyces* spp., *Pseudallescheria boydii*
Actinomycetes	*Nocardiopsis dassonvillei*, *Streptomyces rochei*

tial concentrations were 150 ppm and 140 ppm for ammonia and amines, respectively. For any test case, the removal efficiency rapidly increased for residence times shorter than 1 s, but did not increase much for times longer than 1 s. Additionally, higher removal efficiencies were obtained at 120 Hz than at 60 Hz. Longer residence times and higher frequencies increased the chance of gas molecules being attacked by electrons or radicals, which resulted in higher removal efficiencies. An ammonia removal efficiency and amines removal efficiency of up to 80% and 76%, respectively, were obtained for frequency of 120 Hz and residence time of 2.07 s.

The applied voltage and initial concentration also affected the gas removal efficiency. The ammonia removal when a residence time of 1 s was used is shown in Fig. 4(a). The removal efficiency increased as the applied voltage increased, and the initial concentration did not have a strong effect on the removal efficiency when the applied voltage was higher than 7.5 kV.

The performance of a DBD reactor can also be evaluated using the energy constant, β (J/L), which is defined by the following equa-

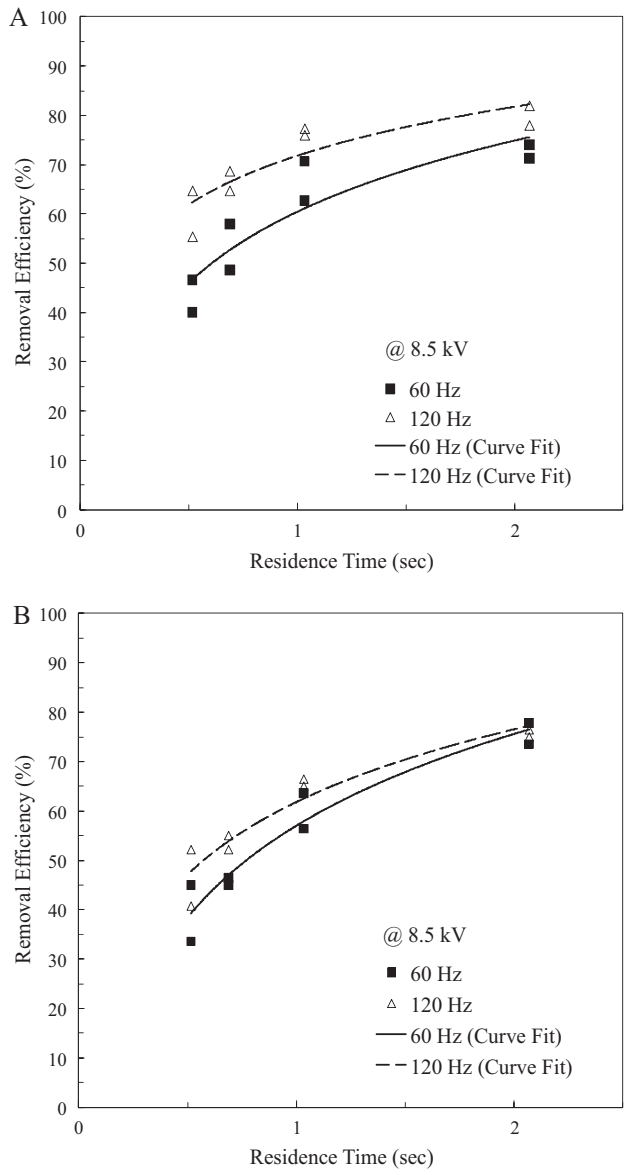

Fig. 3. Removal efficiency of (a) ammonia and (b) amines as a function of gas residence time and frequency.

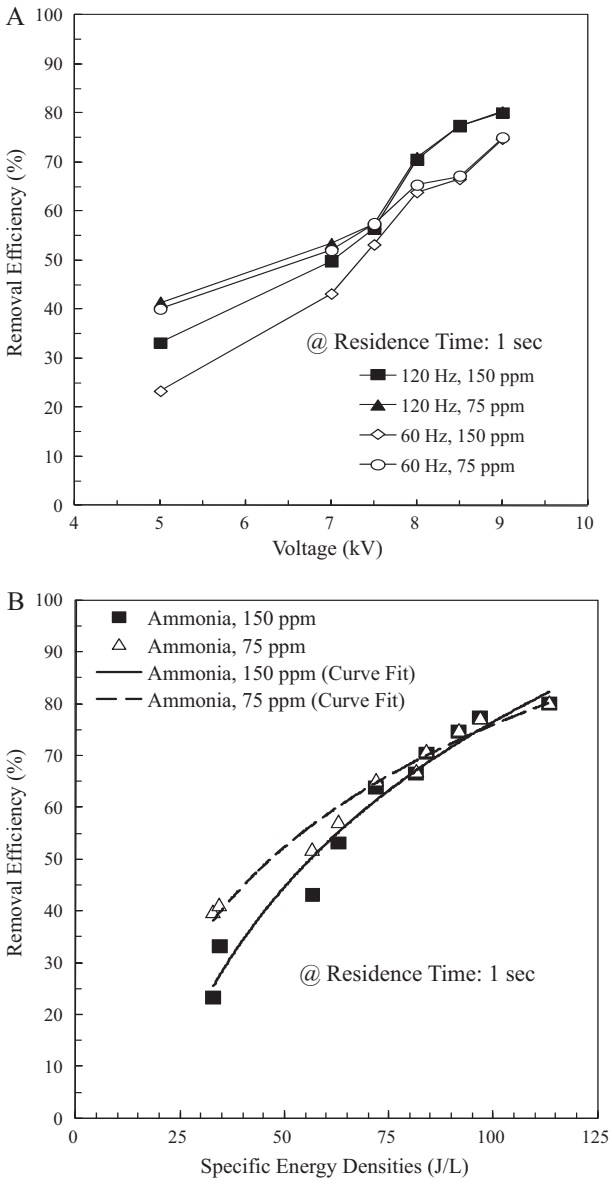

Fig. 4. Effect of (a) applied voltage, initial concentration, and (b) specific input energy on ammonia decomposition.

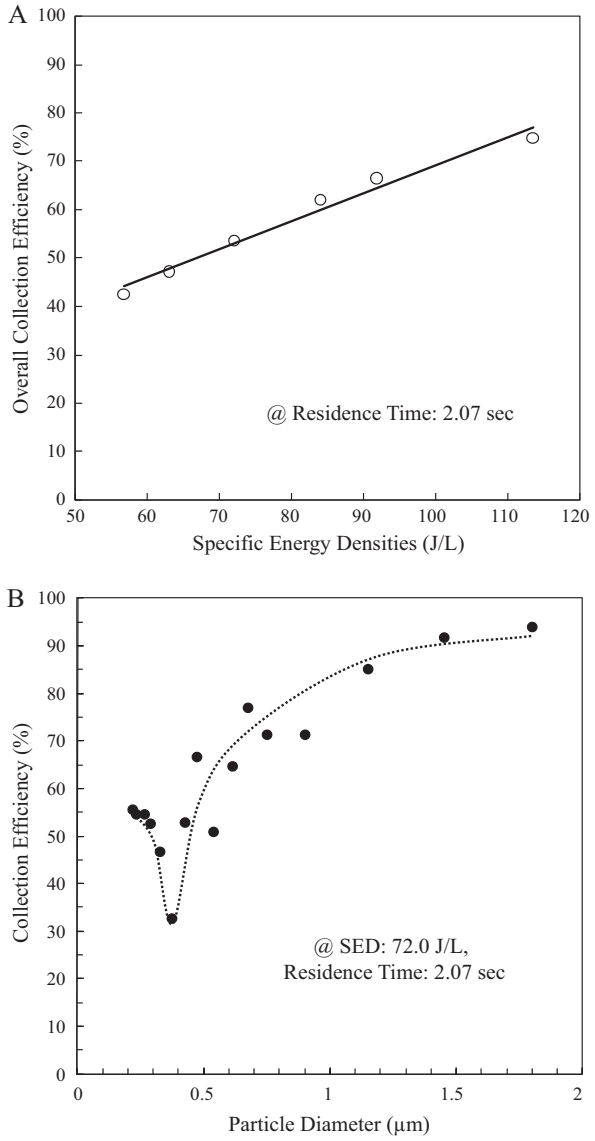

Fig. 5. Collection efficiency of (a) overall airborne particles and (b) airborne particles as a function of the particle diameter.

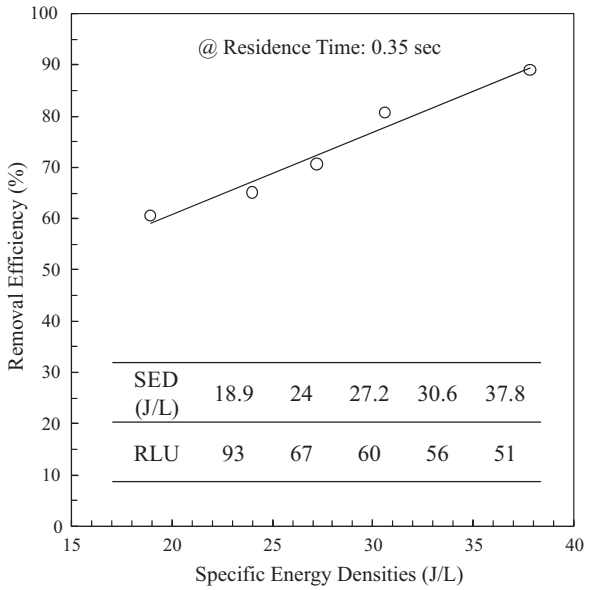

Fig. 6. Bioaerosols removal efficiency and relative luminescent units (RLU) of bioaerosols precipitated on the DBD plate (inset) at 60 Hz when the sampling time was 10 min.

tion [37]:

$$\ln\frac{C_{odor}}{C_{odor,0}} = -\frac{SED}{\beta} \quad (5)$$

$$SED \ \ (\text{specific energy densities}) = \frac{\text{discharge power} \ \ (W)}{\text{gas flow rate} \ \ (L/min)} \times 60\,J/L \quad (6)$$

Fig. 4(b) shows the behavior of ammonia decomposition with SED when the residence time was 1 s. The DBD reactor showed better performance for treating 75 ppm ammonia when the SED was less than 82 J/L. In addition, the removal efficiency increased as the SED increased. The removal efficiencies obtained when 150 ppm and 75 ppm ammonia were treated were about 24% and 40% at an SED of 33 J/L, respectively. When the SED increased to 113 J/L, the removal efficiencies were 80% for both initial ammonia concentrations. The energy constant, β, was found to be 72 J/L and 69 J/L for 150 ppm and 75 ppm ammonia, respectively.

The overall collection efficiencies of airborne particles are plotted as a function of SED in Fig. 5(a). The residence time and the initial concentration of airborne particles were 2.07 sec and 2.1×10^8 particles/m^3, respectively. The results of Fig. 5(a) imply that the AC power applied to the DBD reactor charged the airborne particles, and that the particles were then precipitated on the DBD reactor. Higher SED led to higher overall collection efficiencies because the amplitude of oscillation of airborne particles in a DBD reactor and the particle charging increase as the SED increased. The highest overall collection efficiency was 75% at 113 J/L. The fractional particle collection efficiency at a SED of 72 J/L is plotted in Fig. 5(b) as a function of the particle diameter.

The fractional collection efficiency of the DBD reactor can be expressed using the following equation by assuming a well-mixed flow caused by turbulence [16]:

$$CE_{particle} \ \ (d_p) = 1 - \exp[-k_p EZ] \quad (7)$$

where E is the intensity of the applied electric field and k_p is a constant that is dependent on the flow characteristics. Z is the electrical mobility, which is expressed as [16]:

$$Z \sim \frac{n(d_p)C(d_p)}{d_p} \quad (8)$$

where $C(d_p)$ is the Cunningham correction factor and $n(d_p)$ is the average number of elementary charges of a particle. Even in the presence of electrostatic fields, diffusion charging is the predominant mechanism for charging particles with a diameter of less than about 0.2 μm. For these small particles, Z decreases with increasing d_p; therefore, the collection efficiency decreases as d_p increases. Field charging is the dominant mechanism for particles larger than about 0.2 μm in diameter. For $d_p > \sim 0.2$ μm, Z increases with increasing d_p; thus, the collection efficiency increases as d_p increases [17,38–40]. Therefore, the results presented in Fig. 5(b) indicate that our experimental data explain the dependence of collection efficiency on particle size well.

The bioaerosols removal efficiency of the DBD reactor is plotted in Fig. 6 as a function of the SED. The residence time and the initial bioaerosol concentration were 0.35 s and 600 RLU/m^3, respectively. The removal efficiency increased as the SED increased. In addition to the ATP measurements, we counted the numbers of colonies on the agar plates that contained the sampled and incubated bioaerosols. When the reactor was operated at 31 J/L, the bioaerosols removal efficiency by measuring numbers of colonies was 76%, which was similar to the removal efficiency by measuring RLU (=81%). Yoon et al. [41] have reported that the RLU per sampling

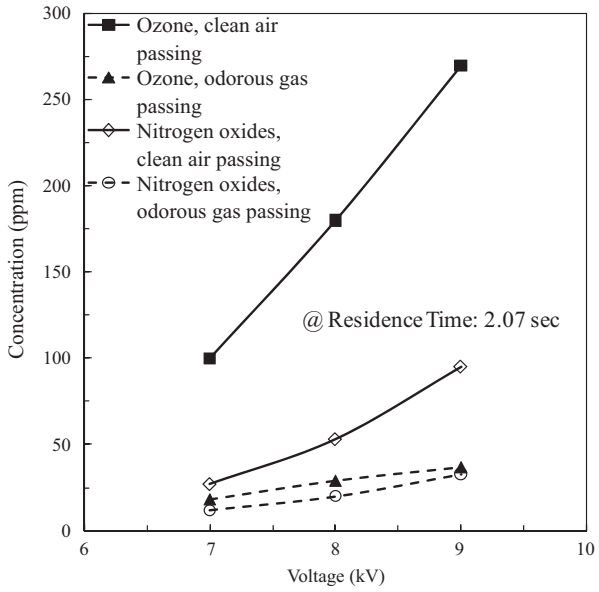

Fig. 7. Concentrations of ozone and nitrogen oxides generated by the DBD when the clean air or odorous gases passed through the DBD reactor.

volume between 29 and 989 RLU/m^3 has a linear relation with the value of CFU per sampling volume. The range of RLU/m^3 measured in this study was 117–600 RLU/m^3.

The bioaerosols that precipitated on the DBD plate when the SED increased from 19 to 38 J/L were measured using an ATP detector. As shown in the table (inset of Fig. 6), the value of RLU decreased as the SED increased. These findings indicate that a higher SED resulted in more bioaerosols being sterilized on the DBD plates.

Ozone and nitrogen oxides are generated from air when a DBD reactor is operated [10,11,14]. Fig. 7 shows the concentrations of ozone and nitrogen oxides generated by our DBD for various experimental conditions. The concentrations of ozone and nitrogen oxides were decreased when odorous gases (ammonia: 150 ppm, and amines: 140 ppm) were passed through the DBD, since the generated ozone and nitrogen oxides reacted with odorous gases. One of the major concerns for removing odorous gases by a DBD reactor is the decomposition by ozone or nitrogen oxides. For example, it has been reported that ammonia is decomposed to NH_4NO_3 by ozone [42], and to NH_4NO_2 and NH_4NO_3 by nitrogen oxides [15,43]. Similarly, amines is decomposed to ammonium nitrates, for example, trimethyl amine may be decomposed to $(N(CH_3)_3H)_2CO_3$, $N(CH_3)_3HNO_2$, and $N(CH_3)_3HNO_3$ by ozone or nitrogen oxides [15,44]. Another possibility for the decrease of generated ozone and nitrogen oxides is the decreased chance of O_2 and N_2 being attacked by electrons. The initial step in formation of ozone and nitrogen oxides is the dissociation of O_2 and N_2 by electrons [45]. However, the chance of the dissociation of O_2 and N_2 when odorous gases exist decreases, since some of the electrons impact molecules of odorous gases.

4. Conclusions

The DBD reactor showed good performance for simultaneously removing odors, airborne particles, and bioaerosols from the air emitted from a municipal composting facility. In this study, the power consumption of the DBD was below 18.9 W when the flow volume of the pollutant gas was 0.2 L and the concentrations of ammonia, amines, airborne particles, and bioaerosols were 150 (or 75) ppm, 140 ppm, 2.1×10^8 particles/m^3, and 1.1×10^4 CFU/m^3, respectively. The removal efficiency of contaminants in the air increased as the SED increased, with ammonia and amines removal efficiencies of up to 80% and 76%, respectively, being obtained. Moreover, the collection efficiency of the overall airborne particles was 75% when 113 J/L of SED was used, while the bioaerosols removal efficiency was 89% when 38 J/L of SED was used.

Acknowledgements

This research was supported by the Converging Research Headquarter for HCE Program funded by the Ministry of Education, Science and Technology (2010K001143).

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