Lab-scale test of a ventilation system including a dielectric barrier discharger and UV-photocatalyst filters for simultaneous removal of gaseous and particulate contaminants

Abstract A ventilation system including a dielectric barrier discharger (DBD) and UV-photocatalyst (UVP) filters was designed and tested for simultaneous removal of gaseous and particulate contaminants in a test chamber. The DBD was used in the first stage of electrostatic precipitator (ESP) for particle charging and gas decomposition. An applied DC electric field was used in the second stage of ESP to collect the charged particles. UVP filters were then used to decompose gaseous species, such as formaldehyde (HCHO) and benzene, toluene, and xylene (BTX) including O_3, which was inherently produced by the DBD. %Reductions in mass concentration of PM2.5 and number concentration of submicron particles were approximately 79.5% and 76.3%, respectively, after the ventilation with air cleaning system was operated for 5 h. Both HCHO and BTX were completely removed when the initial concentration of each gas was 1 ppm.

J. H. Park, J. H. Byeon, K. Y. Yoon, J. Hwang

School of Mechanical Engineering, Yonsei University, Seoul, Korea

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J. Hwang
School of Mechanical Engineering
Yonsei University
Seoul 120-749
Korea
Tel.: +82 2 2123 2821
Fax: +82 2 312 2821
e-mail: hwangjh@yonsei.ac.kr

Practical implications
Indoor air quality (IAQ) problems, such as sick building syndrome (SBS), are caused by limited ventilation in high-rise buildings. To overcome these problems, DBD and UVP filters were applied into a lab-scale ventilation system for simultaneous removal of pollutant particles and gases. The data supplied in this study will be useful for designing any actual ventilation system after further research, including scale-up experiments.

Introduction

Indoor air quality (IAQ) problems, such as sick building syndrome, are caused by limited ventilation in high-rise buildings. To overcome these problems, the effects of air filtration and ventilation on particles have been investigated. A study that compared ventilation systems using an electrostatic precipitator (ESP) and those using fibrous mechanical filters was carried out by Wallace et al. (2004). Howard-Reed et al. (2003) measured the deposition of several kinds of particles of sizes ranging from 0.3 to 10 μm with the central heating and air conditioning fan on or off and with the ESP on or off. They found that only the size and not the composition of the particles affected deposition rates. Fisk et al. (2002) predicted the attainable reductions in the indoor mass concentrations of particles from use of ESP and filters in building supply airstreams. Morawska et al. (2002) experimentally studied the performance of a commercially available two-stage ESP for submicron particles for various airflow rates.

As the filters that are used cause pressure drops and noise problems (Rudnick, 2004) and some ESPs inherently generate ozone (Bitter and Fitzner, 2002; Hautanen et al., 1986), we propose in this paper, a ventilation method using a hybrid clean air system for IAQ. A dielectric barrier discharger (DBD) and UV-photocatalyst (UVP) filters were designed and tested for simultaneous removal of gaseous and particulate contaminants in a test chamber. The DBD was used in the first stage of ESP for particle charging and gas decomposition. An applied DC electric field was used in the second stage of ESP to collect the charged particles. UVP filters were then used to decompose gaseous species such as formaldehyde (HCHO) and

benzene, toluene, and xylene (BTX), including O_3, which was inherently produced by the DBD.

Dielectric barrier discharge produces highly non-equilibrium, controlled plasmas at atmospheric pressure, and can effectively generate atoms, radicals, and excited species with energetic electrons at moderate gas temperatures (Abdel-Salam et al., 2003). The DBD is usually composed of two electrodes, which are separated by a gas gap spacing. At least one of them should be covered with dielectric material. In most DBD configurations operating at atmospheric pressure, tiny short-lived current filaments, called microdischarges, are formed. A large proportion of the electron energy released by microdischarges can be used to dissociate gas molecules and thereby, to produce ions. The wide range of discharge characteristics depend on factors such as DBD geometry, material, type of applied voltage, and so on (Mizuno, 2000). An alternating voltage is typically used to induce microdischarges.

Because the DBD serves as a chemical reactor that produces active chemical species during various reactions, it has been used to remove certain undesired species, interesting for environmental decontaminations. An experimental study on the removal of NOx in flue gas was carried out by Yamamoto et al. (2004), who used plasma chemical reactions in the DBD. Simultaneous removal of SO_2 and NO by use of the DBD was reported by Yamamoto et al. (2000). Rosocha et al. (1994) attempted to remove VOCs and Freon gas by using various types of DBD reactors. Lu et al. (2006) investigated benzene decomposition using a DBD reactor with or without MnO_2 and TiO_2. Moreover, DBD technologies were recently studied for simultaneous removal of fine particulates and gaseous contaminants. Kawada et al. (1999) and Kuroda et al. (2003) attempted to decontaminate fine carbon particles and NOx by using a two-stage ESP, whose typical wire-to-plate charging section was replaced by a DBD. Removal of nanomicron and submicron particles by a DBD was studied by Byeon et al. (2006).

UV-photocatalysts are usually used for decomposition of gaseous contaminants. When the hole-electron, charge carrier pair is formed on the surface of a photocatalyst, the hole makes a hydroxyl radical (•OH), which is a powerful oxidative, or directly oxidizes organics, which are adsorbed on the surface of the photocatalyst, while the electron makes oxygen to oxygen ion (O_2^-), which oxidizes organics and water. VOC is decomposed to CO_2 and H_2O by •OH and O_2^- (Ao et al., 2003). Mills et al. (2003) report that ozone (O_3) can be decomposed by UV-TiO_2 photocatalyst filters. Ginestet et al. (2005) studied on the photocatalytic oxidation air filter for VOC/odor removal.

In this paper, a DBD and UVP filters were applied into a ventilation system for simultaneous removal of pollutant particles and gases. Experimental results for lab-scale tests are presented and discussed.

Experimental

The experimental setup illustrated in Figure 1 consists of a test chamber (A), test particle/gas generation system (B), ventilation with air cleaning system (C), and measurement system (D). The test chamber, which was an airtight cube ($0.5 \times 0.5 \times 0.5$ m) made of acryl, simulated an office building of high population density. A pipe of 65 mm inner diameter was installed at the top of the test chamber for supply air, and the same size pipe was installed for return air. Test aerosol particles and gases (BTX and HCHO) were supplied through three ports (ⓐ, ⓑ, and ⓒ), which were fixed on the pipe. Five sampling probes, made of 6.5φ stainless unit standard, were fixed at the middle of the test chamber. The impaction plate (0.14×0.14 m) was installed 30 mm below the supply air pipe to avoid the direct moving of test particle/gas into the sampling ports. The flow rate of air supplied into the test chamber was determined based on The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 62-1989 (ASHRAE, 1989), which suggests that the total ventilation rate is at least 0.015 m^3/s per person in a living room, and 0.03 m^3/s per person in a smoking room. Assuming that the test chamber is a smoking room and 3 m^3 is occupied by a person, we determined that the minimum ventilation rate of the test chamber was 4.5 m^3/h. Surface velocities of supply air and return air of the test chamber were the same, 0.38 m/s. Eighty per cent of the return air was recirculated to the test chamber and the other 20% was exhausted to the outdoor.

For the experiments of particulate pollutant removal, a steady-state concentration of dioctyl sebacate (DOS) liquid particles was supplied into the test chamber. Particle free compressed air from a dry clean air supply system was distributed to a Collison type atomizer. The test particles were generated from the atomizer of a solution containing DOS. The desired concentrations of test particles were controlled with a laminar flow meter. For gaseous pollutants removal, HCHO and BTX were selected as test gases, as HCHO is a well known source for sick house syndrome problem, and BTX are general VOC sources. HCHO and BTX were generated by two separate bubblers. HCHO was 40 vol.% based on water. BTX had the ratio of 1:1:1. Compressed air of 0.001 m^3/min from a dry clean air supply system was distributed to both bubblers. Bubblers were warm up in water bath to maintain their temperature at 40°C. The desired concentration of each test gas was controlled with both a laminar flow meter and a needle valve before being supplied to the test chamber. The initial concentration of each test gas was set as 1.00 ppm.

The overall schematic of the ventilation with air cleaning system is illustrated in Figure 1. Outdoor air passing through the system was supplied into the test
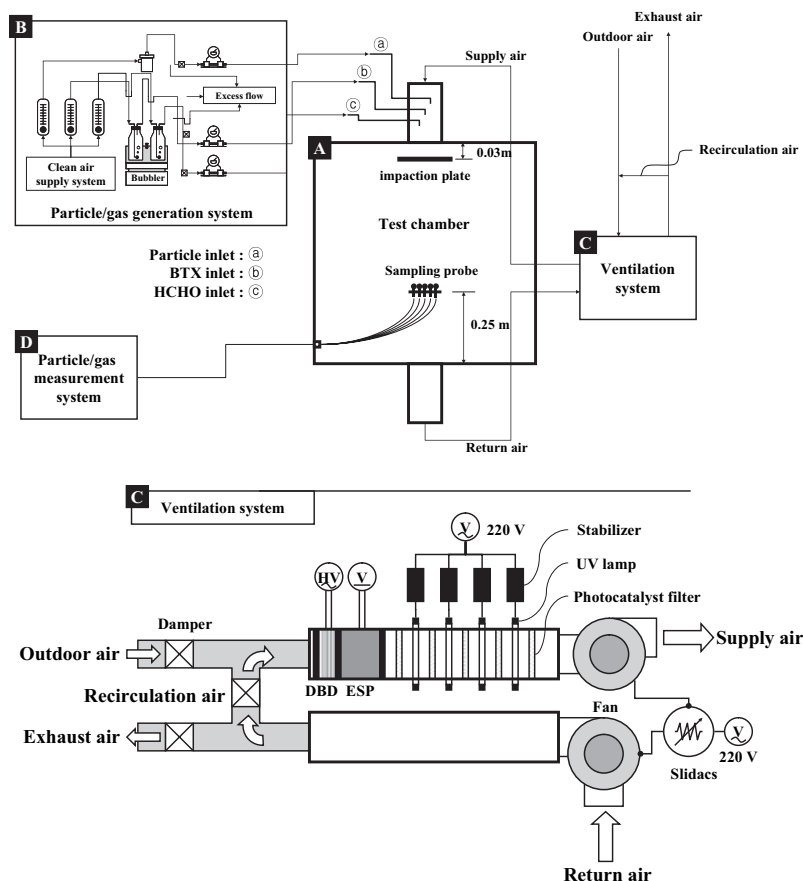
Fig. 1 Experimental setup and ventilation system including a dielectric barrier discharger and UV-photocatalyst filters

chamber by a fan. About 80% of the return air from the test chamber was recirculated into the system by fan, and the other 20% of the return air was exhausted. Airflow rates were controlled with dampers and fans, which were controlled by a slidacs. Acrylic pipes were installed at the back of every damper for monitoring airflow.

The DBD installed in an acryl duct (0.05×0.05 m) consisted of 11 parallel plate electrodes, six of which were grounded. A high, rectangular AC voltage (7.5 kV peak, 60 Hz) was applied to the other five electrodes. This rectangular voltage was chosen over sinusoidal and triangular wave forms because of its linearity to current. The gap spacing between a grounded electrode and its adjacent powered electrode was 4 mm. Each electrode was made of copper foil (50×1 mm, 0.3 mm thickness), sandwiched between two, 0.3 mm thick alumina (Al_2O_3) plates. Non-thermal plasma was formed in the space of the electrodes gap. The test particle/gas with air passed through the plasma region at 0.5 m/s (2 ms of residence time).

The ESP next to the DBD consisted of five, parallel, copper plate electrodes (0.05×0.15 m, 1 mm thickness), three of which were grounded. A high negative DC voltage (-10 kV) was applied to the other two electrodes and drifted particles, which were charged in

the DBD, were deposited on the collecting electrodes. The spacing between a grounded electrode and its adjacent powered electrode was 10 mm. The length of each collecting plate along the streamwise direction was 150 mm, resulting in the airflow residence time of 300 ms.

UV-photocatalyst filters were positioned after the ESP. Four UV-lamps (BLB, λ: 310–400 nm, 4W, F4T5BLB, Sankyo, Tokyo, Japan) were used. Each UV-lamp was activated by an AC power (220 V) via a stabilizer and located between two photocatalyst filters. The distance between a filter and a UV-lamp was 22 mm. The UV intensity at the surface of a filter was approximately 3400 $\mu W/cm^2$, which was measured by a UV Radiometer (UVR-2: Detector Body, UD-36: Sensor, Topcon, Tokyo, Japan). The photocatalyst filter consisted of TiO_2, powdered activated carbon, and zeolite, based on inorganic paper, with the component ratio of 2:5:3. Information about the photocatalyst filter is documented in Table 1. The total depth of photocatalyst filters was 45 mm, resulting in the airflow residence time of 90 ms.

Number and total mass concentration of test particles were measured with a scanning mobility particle sizer (SMPS, TSI3936, Shoreview, MN, USA) and an aerodynamic particle sizer (APS, TSI3021, Shoreview, MN,

Table 1 Information of photocatalyst filter

Size of catalyst bed (L × W × D, mm³)	Cell size (h × p, mm²)	Bed material	Preparation method	Additives (absorber)	Pressure drop (mmAq)
50 × 50 × 9 Model	2.8 × 5.9 Photocatalyst filter Type B	Inorganic paper	Impregnation coating Specific area (m²/g)	Activated carbon, zeolite Inorganic paper (≤ 20) Activated carbon (≤ 1500) Zeolite (≤ 1000)	< 1.00
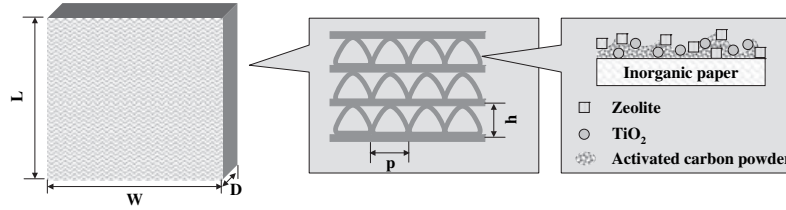
USA), respectively. The SMPS consisted of an aerosol neutralizer (^{210}Po), a differential mobility analyzer (TSI3080, Shoreview, MN, USA), and a condensation particle counter (TSI3022A, Shoreview, MN, USA). Airflow of 0.0003 m³/min in the test chamber was sampled by SMPS while airflow of 0.005 m³/min was sampled by APS. Using SMPS, the number concentration of particles at 14–737 nm in mobility equivalent diameter was measured every 10 min, and using APS, the total mass concentration of particles under 2.5 μm in aerodynamic diameter was measured at the same interval. HCHO and BTX were measured by a TVOC/HCHO analyzer (VH Sniffer II, KINSCO, Seoul, Korea, 0–10 ppm range, 0.01 ppm resolution) every 5 min. In addition, CO/CO_2 analyzer (IAQ-CALC^{TM} IAQ Meters, TSI8762, Shoreview, MN, USA, CO: 0–500 ppm range, 0.1 ppm resolution, CO_2: 0–5000 ppm range, 1 ppm resolution), and O_3 monitor (PortaSensII, Ati, Collegeville, PA, USA, 0–5 ppm range, 0.01 ppm resolution) were used for monitoring CO, CO_2, and O_3 every 5 min, which might be inherently produced by the decomposing gaseous species in the DBD. The temperature and relative humidity of the test chamber were 22.5°C and 50%, respectively.

Results and discussion

Experiments were carried out to investigate the characteristics of our air cleaning system. The total airflow rate to the test chamber was 4.5 m³/h. The data were obtained from repeated measurements and the average values were presented.

Particle removal tests

When the ventilation fan was operated without any air cleaning unit, the steady-state mass concentration of PM2.5 in the test chamber was 504 μg/m³. When the UVP filters were operated in addition to the fan, the mass concentration slightly reduced to 495.7 μg/m³

(1.1%Reduction) at 10 min, 486.6 μg/m³ (2.9%Reduction) at 20 min, and maintained as 483.4 μg/m³ (3.5%Reduction) after 30 min. When the DBD + ESP and the fan were operated but the UVP filters were not, the mass concentration was 190.6 μg/m³ (62.3% Reduction) at 10 min, 141.3 μg/m³ (72.1%Reduction)
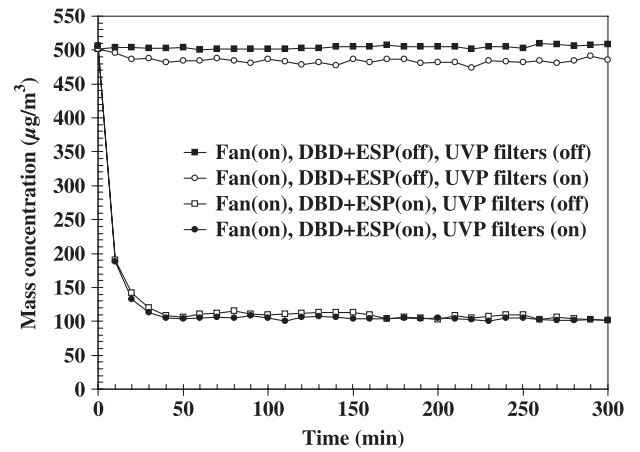
Fig. 2 Temporal variation of mass concentration of PM2.5
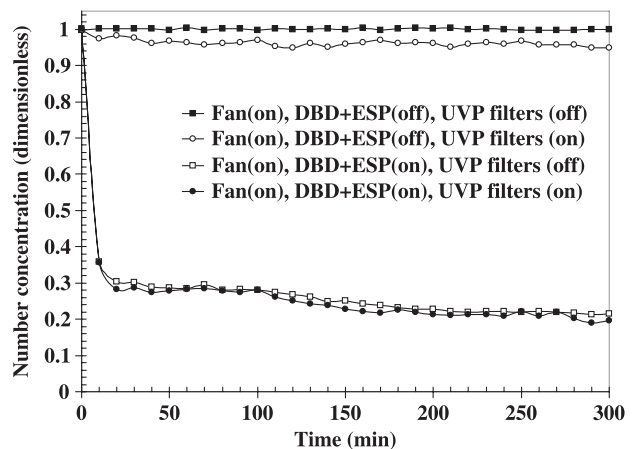
Fig. 3 Temporal variation of number concentration of submicron particles

at 20 min, and maintained as 108.1 $\mu g/m^3$ (78.6% Reduction) after 30 min. When all the air cleaning units were operated with the fan, the mass concentration was 201.1 $\mu g/m^3$ (60.3%Reduction) at 10 min, 132.4 $\mu g/m^3$ (73.8%Reduction) at 20 min, and maintained as 104.1 $\mu g/m^3$ (79.5%Reduction) after 30 min. The results are summarized in Figure 2. The averaged standard deviation of the data was 5 $\mu g/m^3$. The percentage reduction of PM2.5 in the test chamber was calculated from the following equation (Fisk et al., 2002):

$$\%\text{Reduction} = 1 - C/C_{\text{ref}} \qquad (1),$$

where C is the concentration of PM2.5. C_{ref} was chosen as 504 $\mu g/m^3$.

Figure 3 shows the temporal variation of number concentration of submicron particles among the test particles. The averaged standard deviation of the data was 0.01. When the UVP filters were operated with the fan, %Reductions of submicron particles were 2.9% at 10 min, 4.1% at 40 min, and 4.2% at 300 min. When the DBD + ESP were operated with the fan, %Reductions were 64.2% at 10 min, 69.6% at 20 min, and 75.2% at 300 min. %Reductions were 64.5% at 10 min, 71.9% at 20 min, and 76.3% at 300 min, when all the air cleaning units were operated with the fan.

The steady-state removal rate of particles, $\dot{R}_{\text{SS}}$, can be obtained by the following conservation equation:

$$C_O\dot{V}_O + C_S\dot{V}_R - \dot{R}_{\text{SS}} + \dot{G} = (\dot{V}_O + \dot{V}_R) \times C_s \qquad (2),$$

where C_O and C_S are the steady-state concentrations of particles in the outdoor air and in the test chamber, respectively. $\dot{V}_O$ is the volume flow rate of the outdoor air, $\dot{V}_R$ is the volume flow rate of the recirculation air, and $\dot{G}$ is the rate of particle generation. The transient removal rate of particles, $\dot{R}_{\text{TS}}$, is defined as

$$\dot{R}_{\text{TS}} = V_C \times (C_i - C_S)/\tau \qquad (3),$$

where C_i is the initial concentration of particles in the test chamber, V_C is the volume of the test chamber, and

τ is the relaxation time required for the steady state. The clean air delivery rate (CADR) at steady state ($\dot{V}_{\text{CADR}}$) is defined by the equation (McDonald and Ouyang, 2000):

$$\dot{V}_{\text{CADR}} = \eta \times (\dot{V}_O + \dot{V}_R) \qquad (4),$$

where the collection efficiency, η, is

$$\eta = \dot{R}_{\text{SS}}/(C_O\dot{V}_O + C_S\dot{V}_R). \qquad (5)$$

Based on the results in Figures 2 and 3, Equations (2–5) were used to calculate the removal rates and the CADRs for PM2.5 and submicron particles. The results are summarized in Table 2. When the DBD + ESP and the fan were operated but the UVP filters were not, the collection efficiency of submicron particles was 75.7%, which is similar to the results
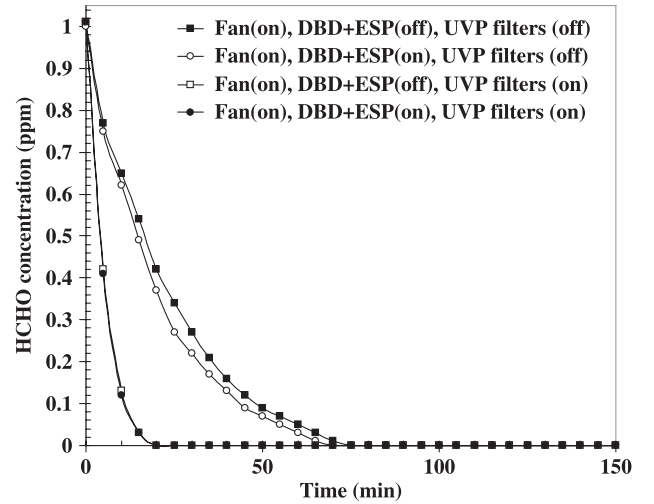
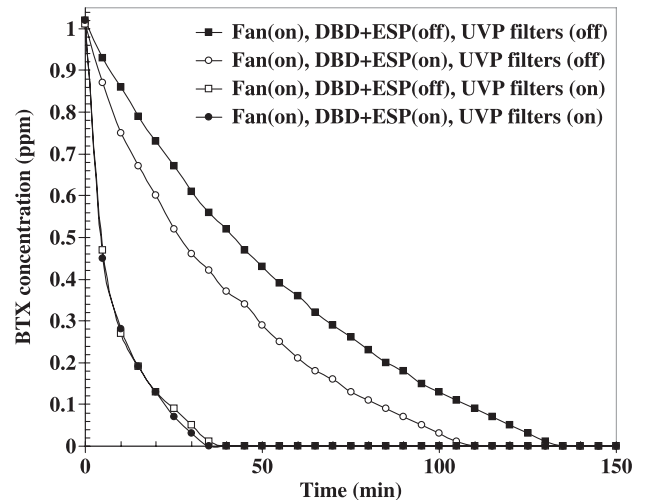**Fig. 4** Temporal variation of formaldehyde concentration

Fig. 5 Temporal variation of benzene, toluene, and xylene concentration

Table 2 Characteristics of air cleaning system for particle removal

System	Characteristics	PM2.5	Submicron particles
Fan (on)	Removal rate (steady state)	16.0 $\mu g/h$	3.1×10^{11} particles/h
DBD + ESP (off)	Removal rate (transient state)	3.3 $\mu g/h$	6.5×10^{10} particles/h
UVP filters (on)	Collection efficiency	0.9%	1.1%
	CADR	0.041 m^3/h	0.043 m^3/h
Fan (on)	Removal rate (steady state)	358.2 $\mu g/h$	6.3×10^{12} particles/h
DBD + ESP (on)	Removal rate (transient state)	96.5 $\mu g/h$	2.4×10^{12} particles/h
UVP filters (off)	Collection efficiency	92.1%	75.7%
	CADR	4.14 m^3/h	3.40 m^3/h
Fan (on)	Removal rate (steady state)	362.1 $\mu g/h$	6.4×10^{12} particles/h
DBD + ESP (on)	Removal rate (transient state)	98.5 $\mu g/h$	2.5×10^{12} particles/h
UVP filters (on)	Collection efficiency	96.7%	80.7%
	CADR	4.35 m^3/h	3.63 m^3/h

CADR, clean air delivery rate; DBD, dielectric barrier discharger; ESP, electrostatic precipitator; UVP, UV-photocatalyst.

obtained by Byeon et al. (2006) and Hautanen et al. (1986) obtained the collection efficiency of two-stage ESP with corona charger, however, for the residence time twice longer than that of our system.

Gas removal tests

Figures 4 and 5 show the temporal variations of HCHO and BTX concentrations, respectively, when the initial concentration of each gas was 1.00 ppm. The averaged standard deviation of the data was 0.02 ppm. When only the ventilation fan was operated, the HCHO was completely removed after 75 min. The additional operation of DBD + ESP did not much affect the removal of HCHO. However, when the UVP filters were operated, the HCHO was completely removed after 20 min, regardless of the operation of DBD + ESP. As illustrated in Figure 5, the UVP filters were also effective for BTX removal. The removal rate of BTX by UVP filters was 1.51 ppm/h, however, which was lower than the HCHO removal rate of 3.03 ppm/h. Only operating a ventilation fan was not enough to remove gaseous pollutant, as discussed by Hodgson et al. (2003). Figures 4 and 5 show that our cleaning system was effective in the removal of gaseous pollutants within a relatively short time of 90 ms.

The effect of the air cleaning system on the generation of unwanted gaseous byproducts was also investigated. Whether the air cleaning system was operated or not, the concentrations of CO and CO_2 were about 4 ppm and 512 ppm, respectively. Even though 0.4–0.7 ppm of ozone was generated when the DBD + ESP was operated with the fan, the additional operation of UVP filters reduced the ozone concentration to 0.01 ppm, which is below the regulation (0.06 ppm in Korea).

Conclusions

A lab-scale ventilation system including a DBD and UVP filters was designed and tested for simultaneous removal of gaseous and particulate contaminants in a test chamber. The DBD was used in the first stage for particle charging and gas decomposition. An applied DC electric field was used in the second stage of ESP to collect the charged particles. UVP filters were then used to decompose gaseous species such as HCHO, BTX, and O_3. %Reductions in mass concentration of PM2.5 and number concentration of submicron particles were approximately 79.5% and 76.3%, respectively, after the ventilation with air cleaning system was operated for 5 h. Both HCHO and BTX were completely removed when the initial concentration of each gas was 1 ppm. The effect of the air cleaning system on the generation of unwanted byproducts such as CO, CO_2, and O_3 was negligible.

Acknowledgement

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