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Design and Performance Evaluation of Plasma Air Cleaning Systems for Removing Yellow Sand Dust

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Abstract−Yellow sand dust (Asian dust storms) causes harmful damage indoors and outdoors during the springtime, and the removal of Yellow sand dust has become an issue for suitable indoor conditions. An air cleaner is required to remove Yellow sand dust efficiently to improve indoor air quality, and the removal characteristics of Yellow sand dust should be studied. The size distribution and mass concentration of Yellow sand dust observed in China and Korea are analyzed, and the removal efficiency of a plasma air cleaning system based on the principle of electrostatic precipitation is evaluated by using Yellow sand dust. Mass median diameter of Yellow sand dust sampled in Beijing and Seoul ranges from 7.0 to 8.0 μm with a mass concentration of 300-1,462 μg/m^3. For a single-pass test, the efficiency of dust removal increases with increasing particle size and decreasing flow rate. The removal efficiency of Yellow sand dust in a plasma air cleaning system at a face velocity of 1.0 m/s is higher than 80%. For a multi-pass test in occupied spaces, the operation time required to reduce Yellow sand dust concentration from an initial concentration of 300 μg/m^3 to 150 μg/m^3 is 10 minutes for a test room of 27 m^3.

Key words: Yellow Sand Dust, Plasma Air Cleaning System, Single-pass Test, Multi-pass Test

INTRODUCTION

In springtime, East Asia, including Korea, China, and Japan, routinely experiences large-scale Yellow sand dust (Asian dust storms) originating from the desert and loess areas in China and Mongolia. The total suspended particulate (TSP) concentration is about twice higher during a dust storm resulting in harmful damage both indoors and outdoors [Lee et al., 1993]. The health impact of Yellow sand dust has come into question from epidemiological studies reporting an association between fine particle concentration and hospital admissions. The removal of Yellow sand dust is now an issue for safe environmental indoor conditions. Therefore, an air cleaner is required to remove this dust efficiently for improving indoor air quality, and a study of the removal characteristics of Yellow sand dust should be conducted. In this paper, the size distribution and mass concentration of Yellow sand dust observed in China and Korea are analyzed. Also, the removal efficiency of a plasma air cleaning system based on the principle of electrostatic precipitation is evaluated using Yellow sand dust.

CHARACTERISTICS OF YELOW SAND DUST

The size distribution of Yellow sand dust ranges from 1.0 to 10.0 μm, and mass median diameter (MMD) ranges from 7.0 to 8.0 μm [Quan, 2001; Lee et al., 1993]. It has been found that the prevailing westerlies transport Yellow sand dust from China to Korea for several days to weeks.

In Korea, normal TSP concentrations range from 87 to 199 μg/m^3 and the mean concentration is 154 μg/m^3, while the maximum TSP concentration increases to 674 μg/m^3 during Yellow sand storms; and the mean concentration is twice of that of normal [Lee et al., 1993]. In Beijing, normal TSP concentration is 198 μg/m^3, while the maximum TSP concentration increases to 1,462 μg/m^3 during Yellow sand storms [Quan, 2001].

DESIGN OF PLASMA AIR CLEANING SYSTEM

A plasma air cleaning system consists of the positive corona pre-

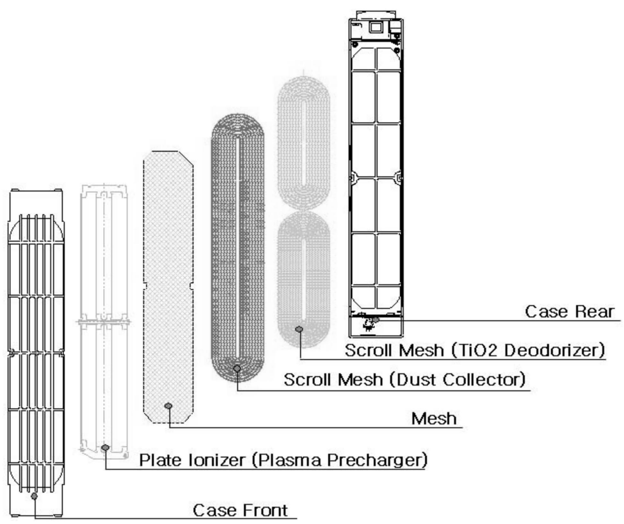

Fig. 1. Schematic diagram of the plasma air cleaning system.

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Table 1. Specifications of the plasma air cleaning system used in this study

Stage	Specifications
Plasma precharger	• Size: 420 (W)×75 (H)×20 (T) mm^3 • Discharge electrode: Tungsten wire (ϕ0.2 mm) • Number of wires: 3 • Distance between grounded electrodes: 23 mm • Dimension of grounded electrodes: 420(H)×20 (W) mm^2 • Applied voltage: (+) 5 kV
Dust collector	• 1^{st} Scroll mesh: Plate-zebra electrode type Size: 400 (W)×75 (H)×11 (T) mm^3 Applied voltages between separators: (+) 3 kV • 2^{nd} Scroll mesh: TiO_2 photocatalyst Size: 180 (W)×75 (H)×6 (T) mm^3 (2ea)

charger upstream of the collector to precharge particles, the scroll dust collector having a grounded electrode plate, and a PET-coated positive plate to collect the precharged particles through the corona precharger (Fig. 1). Table 1 shows the specifications of the plasma air cleaning system consisting of the positive corona precharger and the scroll dust collector.

The precharger unit (420 mm in height, 75 mm in width, and 20 mm in thickness) consists of the discharge electrode of tungsten wire (0.2 mm diameter) placed between grounded plates with a distance of 23 mm. The main function of the precharger in a gas filtration system is to impart the maximum possible charge to the dust particles in the gas stream. By passing through the first stage of the precharger with an applied voltage of +5,000 V, the particles are positively charged.

In the second stage of the plasma air cleaning system, DC voltage of +3,000 V is applied to the PET-coated plates in order to produce an electric field between the PET-coated plates and the grounded plates so that the precharged particulates can be collected on the grounded plates by electrostatic force. For optimal charging and electric stability of the precharger, Coopermans wire-plate charging model is used to determine the design parameters of the precharger, such as the diameter of the discharge electrode, distance of the electrode and the plate, and applied voltage to the electrode [Cooperman, 1960].

EXPERIMENTAL

1. Single-pass Test System

Fig. 2 is a schematic diagram of the single-pass test system which consists of a cross sectional area duct of 120 mm×120 mm, a plasma air cleaning system connected with a filter cartridge, a particle generator, particle samplers to measure the particle number concentrations in the upstream and downstream of the air cleaning system, and a blower controlled by an inverter. The test particles are generated by the atomizer, and passed through the diffusion dryer and the neutralizer (Kr-85) to achieve a Boltzmann equilibrium charge on the particles. The test duct has the main blower downstream of the test device, and the face velocity can be controlled by the frequency inverter. The dust concentrations upstream and downstream of the plasma air cleaning system are measured by particle counters to calculate the filtration efficiency taking into account 2-3% particle loss of dusts supplied in the test duct. The particle counters (Hiac/Royco, FE-80) have four channels to detect the particle sizes of 0.5-1.0, 1.0-2.5, 2.5-5.0 and 5.0-10.0 μm, respectively, and the measurable maximum dust concentration is 5,000,000 particles/ft^3 with a ten to one diluter. One of the two orifices is the mixing orifice of dust and air, and the other is the orifice for measurement of flow rate. The flow rate is controlled by the frequency inverter, and the filtration efficiency is conducted with the face velocity of 0.5, 1.0, and 1.5 m/s.

2. Multi-pass Test System

Fig. 3 is a schematic diagram of the multi-pass test system in occupied spaces for the performance evaluation of the plasma air cleaning system using Yellow sand dust. The experiments are carried out in two rooms, a room of 27 m^3 (4.0 m×2.7 m×2.5 m) with one door and no window and a room of 150 m^3 (8.2 m×7.0 m×2.6 m) with one door and two windows. All doors and windows are closed during the experiments. Yellow sand dust as the standard pollut-

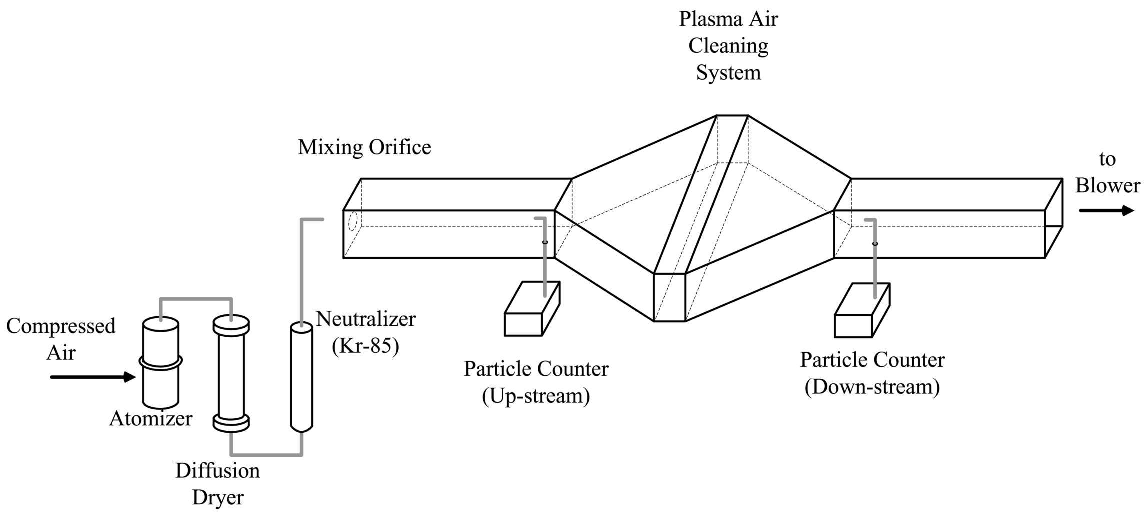

Fig. 2. Schematic diagram of the single-pass test system for measuring the removal efficiency of the air cleaning system.

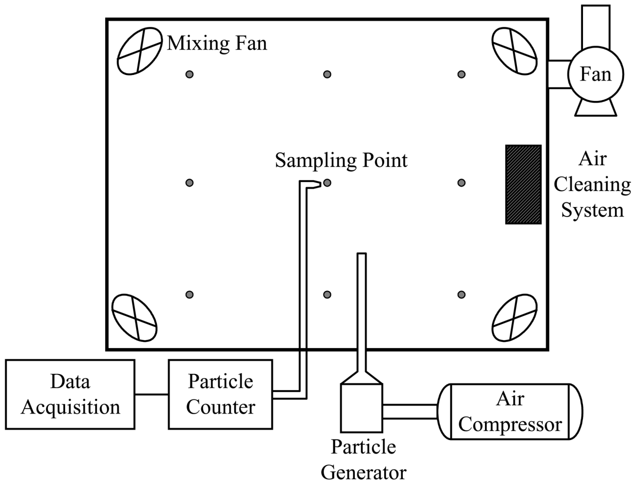

Fig. 3. Schematic diagram of the air handling chamber system for the multi-pass test system.

Table 2. Summary of test conditions for evaluating the performance of the plasma air cleaning system in the multi-pass test system

	Specifications
Air cleaning system	Plasma air cleaning system (Electrostatic precipitation)
Operating mode (Flow rate, Face velocity)	• Maximum (17 m^3/min, 1.5 m/s) • Medium (15 m^3/min, 1.0 m/s) • Minimum (13 m^3/min, 0.5 m/s)
Room size	• 27 m^3 (3.0 m×3.0 m×3.0 m) • 150 m^3 (8.2 m×7.0 m×2.6 m)
Temperature	20-26 °C
Relative humidity	40-65%
Test particle	JIS test dust (MMD: 7.0 μm)
Initial concentration	300 μg/m^3

ants is generated inside the test room with the particle generator, and dispersed uniformly by four mixing fans located in each corner. The number concentration and mass concentration of test particles are monitored by the particle counters (Hiac/Royco, FE-80) and the detector (Casella, Microdust) for measuring the mass concentration, respectively. The sampling probe is located at the center of the test room. The indoor temperature and the relative humidity are 20-26 °C and 40-65%, respectively. Test conditions for evaluating the performance of the plasma air cleaning system in the multi-pass test system are summarized in Table 2.

3. Test Dusts

Table 4. Particle removal efficiencies of the plasma air cleaning system as a function of particle size

Face velocity (m/s)	Removal efficiency (%)			
	0.5-1.0 μm	1.0-2.5 μm	2.5-5.0 μm	5.0-10 μm
0.5	91.60	94.39	95.71	95.98
1.0	82.05	87.18	87.79	89.81
1.5	73.88	80.37	79.45	82.53

Note: Data of removal efficiency shown in the table are average values of 5 test data having error limits of ±3%.

Table 3 shows the material properties of test dusts, JIS test dust #8, which is a representative and equivalent dust to Yellow sand dust. JIS test dust #8 has a size distribution of 0.1-10.0 μm with a mass median diameter of 6.6-8.6 μm and particle density of 2.9-3.1 g/cm^3. It consists of similar chemical components as Yellow sand dust. From this result, it is acceptable to use JIS test dust #8 as the equivalent to Yellow sand dust.

The electrical resistivity is the most important characteristics of the particle in the design of the electrostatic precipitator, and it can be the barometer to determine the dust collection efficiency of the electrostatic precipitator. The values of electrical resistivity can be classified into three group of low resistivity ($<10^4$ Ω·cm), normal resistivity (10^4-10^{10} Ω·cm), and high resistivity regime ($>10^{10}$ Ω·cm). In this study, the electrical resistivities of Yellow sand dust and JIS test dust #8 are measured to be in the normal resistivity regime by Japanese Industrial Standard (JIS B 9915) [Lee et al., 2001]. The values of electrical resistivity measured by Japanese Industrial Standard (JIS B 9915) for Yellow sand dust and JIS test dust #8 are 1.0-2.5×10^7 Ω·cm, and 1.5-3.0×10^7 Ω·cm, respectively. From a similar result for electrical resistivity for two dusts, the plasma air cleaning system can be expected to be suitable for the removal of Yellow sand dust since the resistivity of Yellow sand dust is in the regime of normal resistivity.

RESULTS AND DISCUSSION

1. Single-pass Efficiency of the Plasma Air Cleaning System

Table 4 shows the removal efficiencies of the plasma air cleaning system for Yellow sand dust as a function of particle size and face velocity. The particle number concentration is 50,000 particles/ft^3. The removal efficiency of test particle can be calculated by comparing with the particle number concentration between upstream and downstream of the plasma air cleaning system for the size range of each particle. For the face velocity of 1.0 m/s, the removal efficiency of dusts is higher than 80% for the entire range of particle

Table 3. Material properties of test dusts similar to Yellow sand dust

	Yellow sand dust	JIS test dust #8
Density (g/cm^3)	2.7-3.2	2.9-3.1
Mass median diameter (μm)	7.0-8.0	6.6-8.6
Size distribution (μm)	0.1-10.0	0.1-10.0
Material components	SiO_2, Al_2O_3, Fe_2O_3, CaO	SiO_2, Al_2O_3, Fe_2O_3, CaO
Electrical resistivity (10^7 Ω·cm)	1.0-2.5	1.5-3.0

size. The dust removal efficiency increases with increasing particle size and decreasing face velocity. It is believed that the lower face velocity causes a longer retention time of the particles in the collection region of the plasma air cleaning system, and the particles can be removed more easily compared with the case of high face velocity. The plasma air cleaning system based on the principle of the electrostatic precipitator is suitable for the removal of Yellow sand dust. It is believed that the resistivity of the Yellow sand dust is 1.5-3.0×10^7 Ω·cm representing the normal operation range of the electrostatic precipitator.

2. Multi-pass Efficiency of the Plasma Air Cleaning System

Fig. 4 shows the removal efficiency of dust number concentration as a function of operating time of the plasma air cleaning system for the multi-pass test in the air handling chamber system of 27 m^3 and 150 m^3. Four tests are conducted with respect to the operating mode such as the natural decay, the minimum mode (the flow rate of 13 m^3/min), the medium mode (the flow rate of 15 m^3/min), and the maximum mode (the flow rate of 17 m^3/min). JIS test

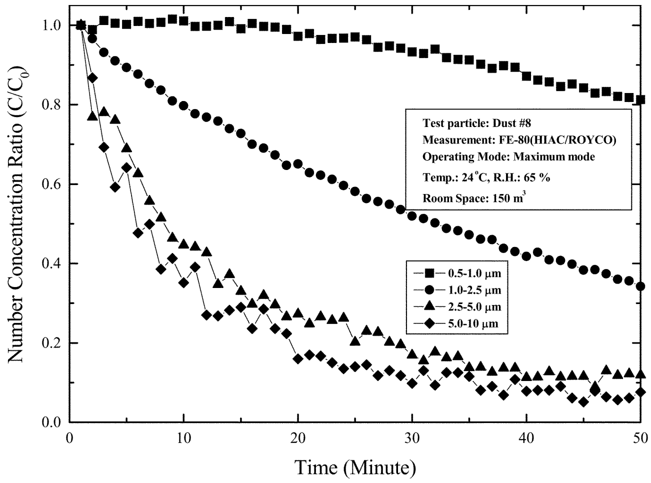

Fig. 5. Removal efficiency of the test dusts for the multi-pass test in the air handling chamber system as a function of particle size.

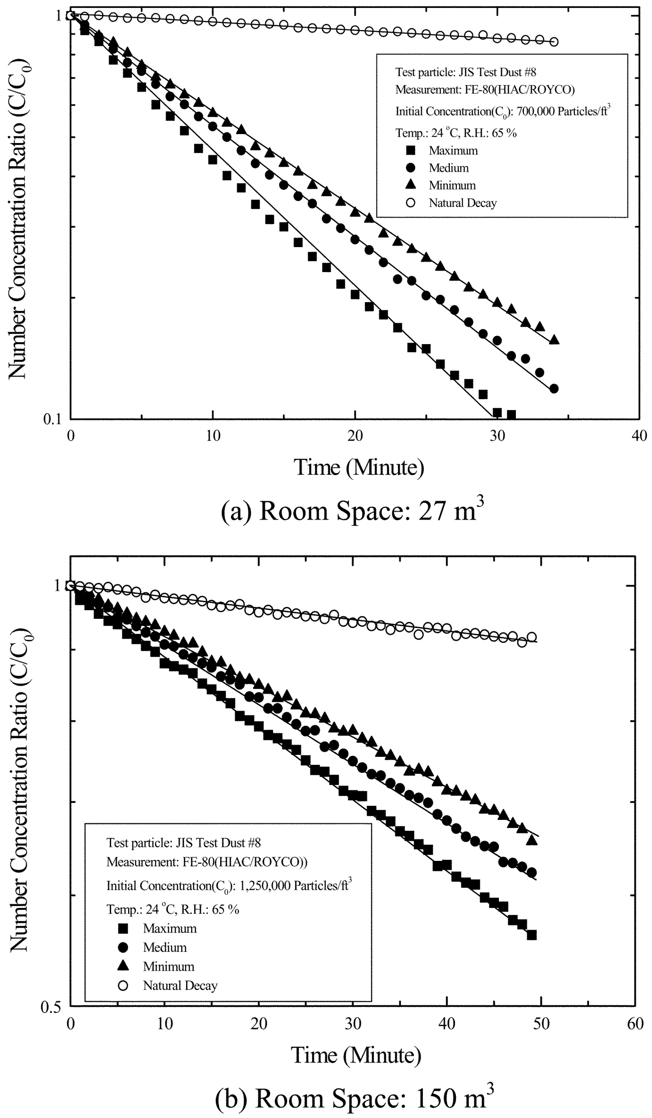

Fig. 4. Removal efficiency of the test dusts for the multi-pass test in the air handling chamber system.

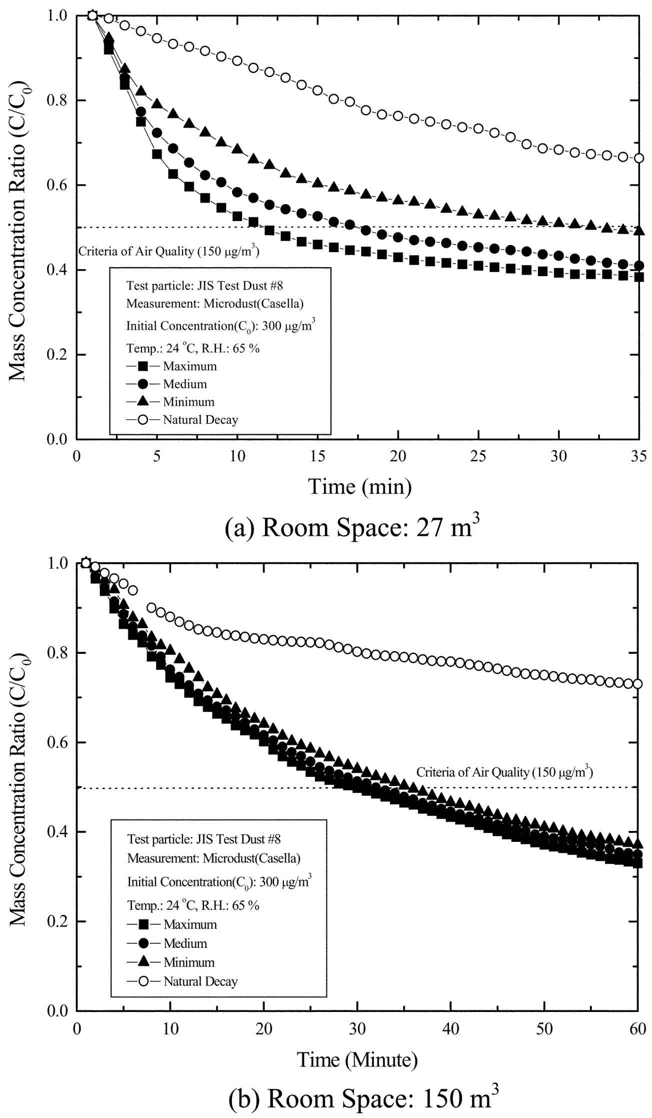

Fig. 6. Removal efficiency of dust mass concentrations for the multi-pass test in the air handling chamber system.

dust #8 is used as the indoor pollutants and measured by the optical particle counter. The fit constants, which indicated a decreased rate of dusts, in a room of 27 m^3 for natural decay, the minimum mode, the medium mode, and the maximum mode are 0.0042, 0.0558, 0.0632, and 0.0755 (min^{-1}), respectively. As shown in the results, the number concentration of test particles decreases exponentially with increasing operating time, and the decay constant increase with increasing of the flow rate of the air cleaning system. It is believed that the pollutant concentration decreases rapidly in case of the high flow rate due to the high ventilation rate of the air cleaning system in spite of its low single pass efficiency.

Fig. 5 shows the removal efficiency of dust number concentration as a function of particle size for the multi-pass test in the air handling chamber system of 150 m^3 at the maximum mode (17 m^3/min flow rate). Particles larger than 2.5 μm in size can be removed easily because they have relatively large surface area to contact with the ions, while particles smaller than 2.5 μm show low efficiency of the dust removal due to relatively low surface area for particle charging.

Fig. 6 shows the dust removal of mass concentration as the operating time of the plasma air cleaning system for the multi-pass test in the air handling chamber system of 27 m^3 and 150 m^3. The operation times required to reduce Yellow sand dust concentration from the initial concentration of 300 μg/m^3 to 150 μg/m^3 for the test room of 27 m^3 and 150 m^3 are 10 and 30 minutes, respectively.

CONCLUSIONS

Yellow sand dust causes harmful damage indoors and outdoors during the springtime. The removal of Yellow sand dust using an air cleaning system has become an issue for suitable indoor conditions. The removal efficiency of a plasma air cleaning system based on the principle of electrostatic precipitation is evaluated by using Yellow sand dust for improving indoor air quality.

For the single-pass test, the removal efficiency of Yellow sand dust in the plasma air cleaning system at a face velocity of 1.0 m/s is higher than 80%. It is believed that the resistivity of the Yellow sand dust is $1.5\text{-}3.0\times10^7$ Ω·cm representing the normal operation range of the electrostatic precipitator. The efficiency of dust removal increases with increasing particle size and decreasing flow rate.

For a multi-pass test in occupied spaces, the operation time required to reduce Yellow sand dust concentration from the initial concentration of 300 μg/m^3 to 150 μg/m^3 is 10 minutes for the test room of 27 m^3. The number concentration of test particles decreases exponentially with increasing operating time.

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