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Removal of particulate matter from an air stream by a packed dielectric barrier discharge

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Abstract−This study elucidates the feasibility of using a packed dielectric barrier discharge approach to remove particulate matter from an air stream. The experimental results reveal that the particle removal efficiency of the packed dielectric barrier discharge system rose to 92.2% for 0.3 μm particles as the discharge voltage was increased to 20 kV at an operating frequency of 60 Hz. Only when the discharge voltage was sufficiently high to remove particulate matter did the particle removal efficiency increase with the operating frequency. The power required to adjust the discharge voltage was less than that required to adjust the operating frequency at the particular removal efficiency. Accordingly, energy can be saved in a packed dielectric barrier discharge system by adjusting the discharge voltage rather than the operating frequency to remove particulate matter from the air stream.

Key words: Dielectric Barrier Discharge, Particulate Matter, Removal Efficiency

INTRODUCTION

Plasma processes have in recent years been extensively adopted in various industries, including the electronic industry and the microcircuit fabrication industry [1-3]. A non-thermal plasma reactor has also been used in air pollution control systems to remove mixed air pollutants [4-6]. The dielectric barrier discharge approach is a non-thermal plasma procedure that produces free electrons to generate free radicals, ions and metastables in a reaction zone by applying high voltage discharge. These products are all chemically active and destroy toxic molecules. Therefore, dielectric barrier discharge can be employed to remove undesired species from an air stream for environmental applications, including nitrogen oxides [6,7], sulfur oxides [8,9] and volatile organic compounds [10-14].

Dielectric barrier discharge approaches have been examined for their ability to remove particulate matter from diesel exhaust [1,15-17]. Chae [16] investigated the use of a non-thermal plasma technique to treat diesel exhaust. His results indicated that the non-thermal plasma reactor influences the oxidation of particulate matter in diesel exhaust at low temperature. Dan et al. [1] revealed that the efficiency of removal of particulate matter from the diesel exhaust by the non-thermal plasma technique ranged from 25 to 57%. Filling the discharge gap with Cu-ZSM-5 catalyst pellets promoted the removal of particulate matter. Yao et al. [17] noted that the particulate matter from diesel engines can be removed by using uneven dielectric barrier discharge reactors. The maximum fraction of particulate matter removed was 67% using 300 W energy injections and a dielectric barrier discharge reactor with a gap distance of 0.4 mm. The particle removal efficiency can be increased by reducing the width of the gap in the dielectric barrier discharge reactor.

Human exposure to indoor particulate matter has attracted substantial interest [18,19]. Numerous commercial devices are available for removing particulate matter from indoor air, including filtration and electrostatic precipitation. An advanced indoor air cleaning system must have a bacterial, odor and VOC control instrument, as well as a mechanism for removing particulate matter. In some cases, the dielectric barrier discharge reactor acts as a combined electrostatic precipitation, UV source and chemical decomposition reactor to treat mixed air pollutants [20]. It is worthwhile to know the removal of particulate matter by using a dielectric barrier discharge reactor in indoor environments.

This investigation experimentally studied the removal efficiency of particulate matter from an air stream using a packed dielectric barrier discharge system at low and high discharge voltages. The particle removal efficiencies obtained using the packed system without discharge were also determined for comparison. The effect of the operating frequency on the removal efficiency of the particulate matters was examined for various particle diameters and discharge voltages. Finally, the relationship between the required power and the particle removal efficiency of the packed dielectric barrier discharge system was investigated at various discharge voltages and operating frequencies.

EXPERIMENTAL

This work experimentally determined the particle removal efficiency of a packed dielectric barrier discharge system at various discharge voltages and operating frequencies. Fig. 1 schematically depicts the experimental system. The 5 mm nonporous glass pellets were placed in a wire-tube dielectric barrier discharge reactor between two electrodes. This dielectric barrier discharge system consisted of a Pyrex-glass tube (I.D.=2.0 cm) and a stainless steel wire (0.5 cm in diameter) that was suspended along the axis of the tube and served as an inner electrode. The grounding electrode was made of stainless steel wire mesh and was wrapped around the outside of the glass tube. The effective discharging length was 6.5 cm. High pulsed voltages with adjustable frequencies from 60 to 150 Hz and adjustable amplitudes from 0 to 20 kV were applied to the inner electrodes to generate plasma to test the efficiency of removal

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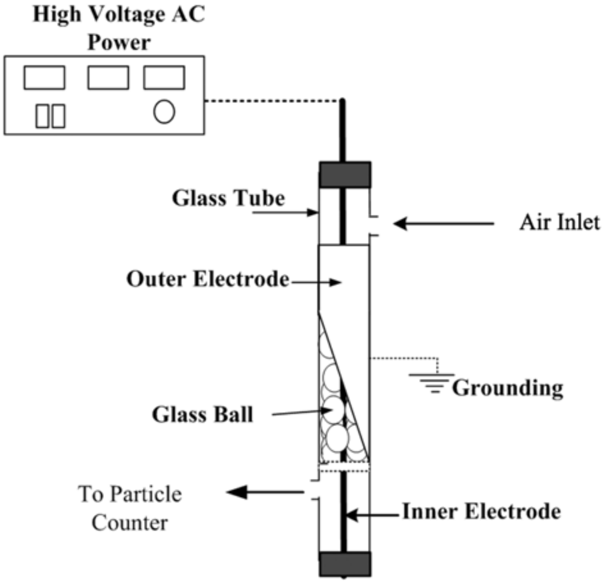

Fig. 1. Experimental setup of packed dielectric barrier discharge system.

of particulate matter from an air stream.

The particle size distributions were measured with multi-stage micro-orifice uniform deposit impactors (MOUDI, Model 100, MSP Corp.). The MOUDI has ten stages, with the following nominal 50% cutoff points: after-filter, 0.1 μm, 0.18 μm, 0.32 μm, 0.56 μm, 1.0 μm, 1.8 μm, 3.2 μm, 5.6 μm, 10 μm and inlet (18 μm). The MOUDI adopted Teflon filters as substrates and the flow rate was approximately 30 L/min. A Chemcomb Cartridge (Model 3500, Rupprecht & Patashnick Co., Inc. NY, USA) sampler was used to determine the mass concentration of PM_{10} (which is particulate matter with an aerodynamic diameter of less than 10 μm). The components of the Chemcomb Cartridge sampler included an impactor with a cutoff aerodynamic diameter of 10 μm, a glass-transition section, two honeycomb denuders, a spacer and a filter pack. In this investigation, a Teflon filter was placed downstream of the denuders to collect the particulate matter. The flow rate in the Chemcomb Cartridge was 10 L/min. The MOUDI and the Chemcomb Cartridge samplers were conducted over 24 hours. The samples of the MOUDI and the Chemcomb Cartridge sampler were pre- and post-weighed with a microbalance (Mettler Toledo Inc, Greifensee, Switzerland) after 24 hours of equilibration at 23±3 °C and a relative humidity of 40±5%. During the tests, the ambient temperatures ranged from 27.4 °C to 31.7 °C, and the ambient RH ranged from 64.2% to 73.5%.

An optical particle counter (LASAIR II, Particle Measuring Systems Inc., Boulder, Colorado, USA) was used to measure the number concentrations of particles at the inlet and the outlet of the packed dielectric barrier discharge reactor to determine the efficiency of removal of the particulate matter. LASAIR II is a portable, durable and lightweight aerosol counter that measures particles of size 0.3 to 25.0 μm using six channels (0.3, 0.5, 1.0, 5.0, 10.0 and 25.0 μm). A laser beam was projected through the sample chamber of the LASAIR II and was scattered from the particulate matter in the air stream of the chamber. The scattered light was picked up by using a collecting photo detector and converted to a voltage pulse that corresponded to the size of the particulate matter. The inlet particle concentration in the air stream was measured with the LASAIR II, and the outlet particle concentration was measured after the air had passed through the packed dielectric barrier discharge system. The sample flow in the packed dielectric barrier discharge system was fixed at 28.3 L/min. The duration of each sampling was 30 s, and a delay of 10 s was required before the downstream concentration was measured. After the outlet concentration had been measured, the inlet concentration was measured again to verify the steadiness of particle concentration. The steadiness of the particle concentration was within 4.6%. Each data point under a particular test condition for a particle size was the mean over three measurements. The particle removal efficiency of the dielectric barrier discharge reactor was calculated to be one minus the outlet particle concentration divided by the inlet particle concentration.

RESULTS AND DISCUSSION

1. Particle Removal Efficiency

Fig. 2 plots the particle removal efficiency of the packed dielectric barrier discharge as a function of particle diameter for low discharge voltages (0-12 kV) at an operating frequency of 60 Hz. Without a discharge voltage, larger particles were collected on the glass beads, corresponding to higher removal efficiency, while the smaller particles remained in the air with lower removal efficiency. When the particle-laden stream entered the glass pellets in the packed dielectric barrier discharge system, the particle collection efficiency increased with the particle size due to gravitation and the mechanism of impact of larger particles [21]. In this study, the distribution of particle sizes was bimodal and the PM_{10} mass concentration ranged from 73 to 82 μg/m^3. The mass median diameter and the geometric standard deviation of the fine particles were measured to

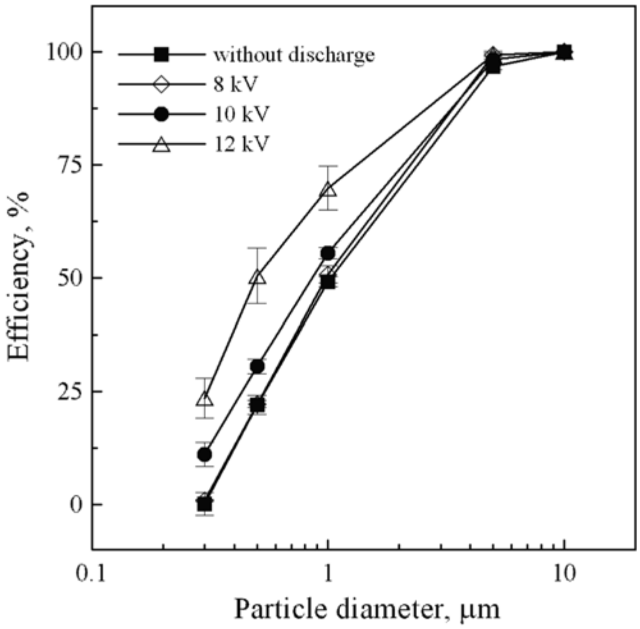

Fig. 2. Removal efficiency of packed dielectric barrier discharge system versus particle diameter at low discharge voltages (0, 8 kV, 10 kV, 12 kV).

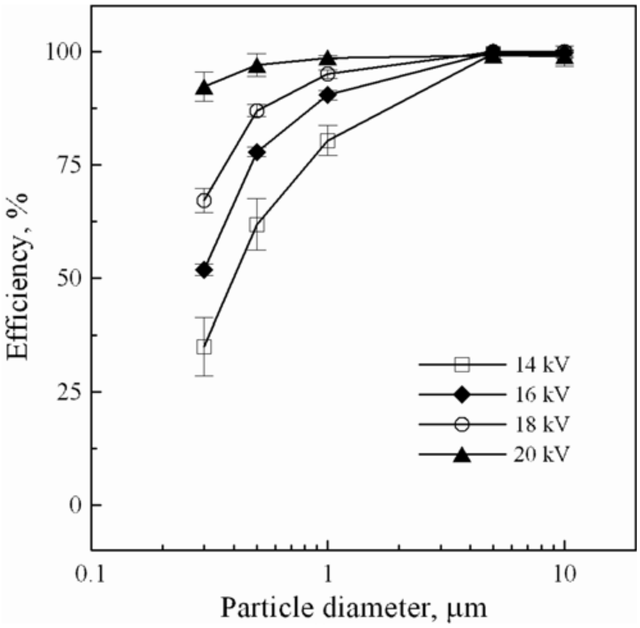

Fig. 3. Removal efficiency of packed dielectric barrier discharge system versus particle diameter at high discharge voltages (14 kV, 16 kV, 18 kV, 20 kV).

be 0.32-0.39 μm and 1.24-1.33, while those of the coarse particles were 3.5-3.8 μm and 1.52-1.58, respectively. The results reveal that the particle removal efficiency of the 8 kV discharge voltage was close to that of 0 kV, because a discharge voltage of 8 kV did not suffice to remove the particulate matter from the air stream. At a 10 kV discharge voltage, the particle removal efficiency slightly exceeded that at the 8 kV discharge voltage. As the discharge voltage was increased from 10 kV to 12 kV, the particle removal efficiency increased from 30.6% to 50.4% for a particle diameter of 0.5 μm.

Fig. 3 plots the particle removal efficiency of the packed dielectric barrier discharge system at high discharge voltages (14-20 kV). The results reveal that the particle removal efficiency increased with the discharge voltage for a range of particle diameters. For instance, the particle removal efficiency increased from 34.9% to 67.1% as the discharge voltage increased from 14 kV to 18 kV for a particle diameter of 0.3 μm, and increased from 80.3% to 94.9% for 1.0 μm particles. The particle removal efficiency increased to 92.2% and 98.6% as the discharge voltage was increased to 20 kV, rose for 0.3 μm and 1.0 μm particles, respectively, because an increase in the discharge voltage of the packed dielectric barrier discharge system increased the strength of the ionic wind, and strengthened the attraction of particles by the glass beads. Hence, the particulate matter is more easily removed by a higher discharge voltage. The results also demonstrate that the particle removal efficiency increased with the particle diameter, because the particle electrical mobility was proportional to the square root of the particle diameter [22].

2. Effect of Operating Frequency

Fig. 4 plots the effect of the operating frequency on the efficiency of removal of particles by the packed dielectric barrier discharge system with a discharge voltage of 12 kV. The figure reveals that the particle removal efficiency increased with the operating frequency for various particle diameters. The particle removal efficiency increased from 23.5% to 91.2% for 0.3 μm particles and from 69.8% to 96.1% for 1.0 μm particles as the operating frequency was increased from 60 Hz to 150 Hz. These results demonstrate that increasing the operating frequency effectively improved the particle removal efficiency at a discharge voltage of 12 kV because the probability of collision between the particulate matter and the packed glass balls increased in the small gap in the packed dielectric barrier discharge system, increasing the deposition rate of the particulate matter [17]. However, for a 10 kV discharge voltage, the particle removal efficiency at an operating frequency of 150 Hz was close

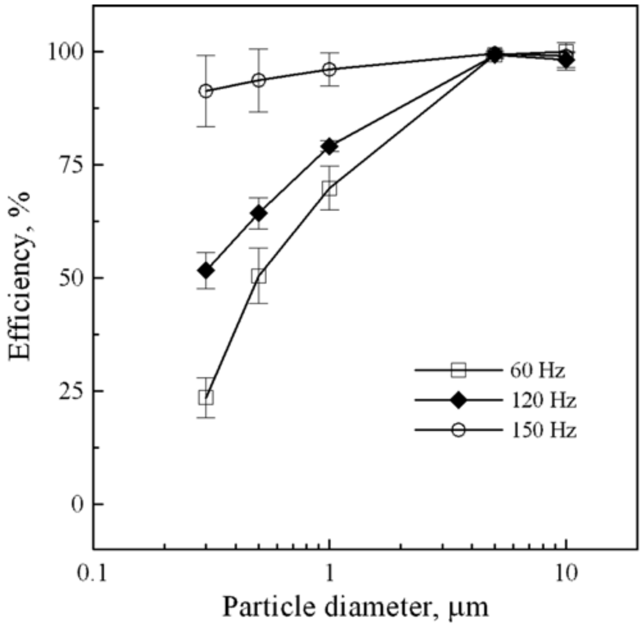

Fig. 4. Influence of operating frequency on particle removal efficiency at discharge voltage of 12 kV.

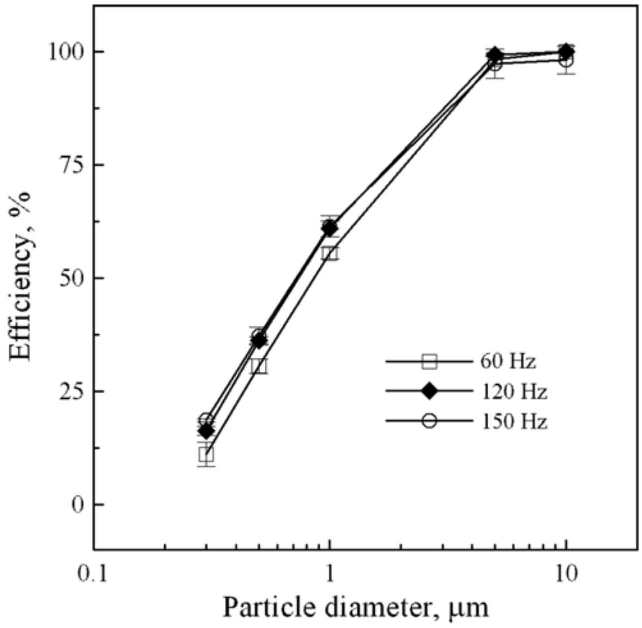

Fig. 5. Influence of operating frequency on particle removal efficiency at discharge voltage of 10 kV.

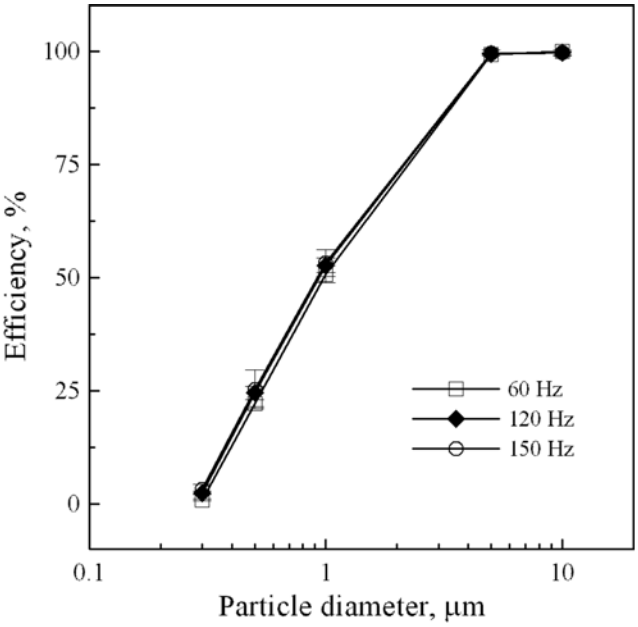

Fig. 6. Influence of operating frequency on particle removal efficiency at discharge voltage of 8 kV.

to that at 120 Hz, and slightly exceeded that at 60 Hz, as presented in Fig. 5. Fig. 6 depicts similar results, and shows that the particle removal efficiencies at operating frequencies of 60 Hz, 120 Hz and 150 Hz were close to each other at a discharge voltage of 8 kV. This may be attributed to the fact that discharge voltages of 8 kV and 10 kV were ineffective in eliminating particulate matter from the air stream at various operating frequencies. Using a discharge voltage of 12 kV increased the particle removal efficiency of the packed dielectric barrier discharge system at various operating frequencies. The results show that the discharge voltage of the packed dielectric barrier discharge system dominated the removal efficiency of the particulate matter. Restated, when the discharge voltage was effective for removing particulate matter, it would be effective by increasing the operating frequency of the packed dielectric barrier discharge system.

3. Input Power

Figs. 7 (particle diameter=0.3 μm) and 8 (particle diameter=1.0 μm) plot the input power of the packed dielectric barrier discharge system for removing particulate matter at various operating frequencies (60 Hz, 120 Hz and 150 Hz) and various discharge voltages (8 kV, 10 kV and 12 kV). Fig. 7 demonstrates that the input power of the packed dielectric barrier discharge system increased as the particle removal efficiency was improved at a 12 kV discharge voltage. This result shows that the particle removal efficiency increased with the operating frequency, and the input power was higher at a discharge voltage of 12 kV than at other discharge voltages. The increase in the input power was considered to be one of the determinants for the effectiveness of the particle removal by the packed dielectric barrier discharge system. The results are similar to those of Dan et al. and Yao et al., who reported that the efficiency of removal of particulate matter increased with the energy input [1,17]. The particle removal efficiency did not obviously increase with the operating frequency at discharge voltages of 8 kV and 10 kV, but it did at a discharge voltage of 12 kV. For instance, the particle removal efficiency increased only from 0.9% to 3.2% and from 11.1% to 18.6%, even though the input power was increased from 4 W to 15.4 W and from 5.2 W to 25.8 W for discharge voltages of 8 kV and 10 kV, respectively. The gradients of the linear regression at discharge voltages of 8 kV and 10 kV were 0.2 and 0.351 were lower than that, 2.19, at a discharge voltage of 12 kV. The increase in input power did not clearly increase the particle removal efficiency of the packed dielectric barrier discharge system,

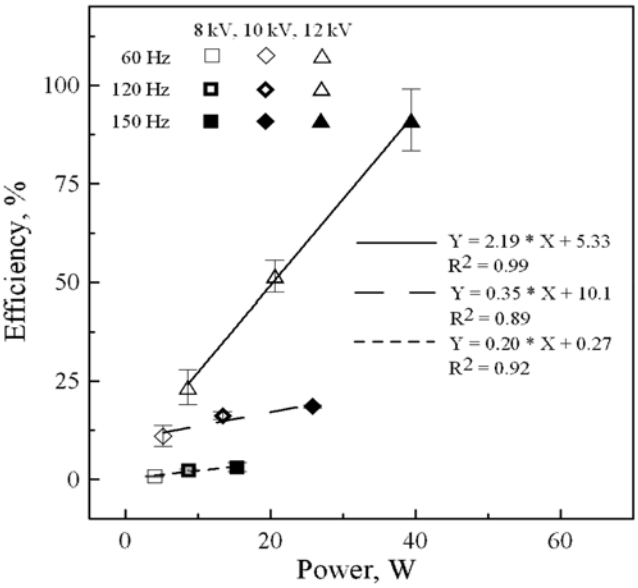

Fig. 7. Particle removal efficiency versus input power of packed dielectric barrier discharge system for various discharge voltages and operating frequencies at particle diameter of 0.3 μm.

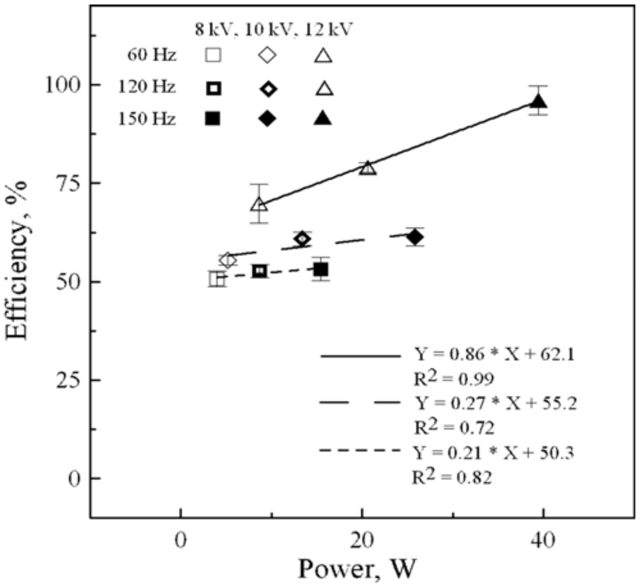

Fig. 8. Particle removal efficiency versus input power of packed dielectric barrier discharge system for various discharge voltages and operating frequencies at particle diameter of 1.0 μm.

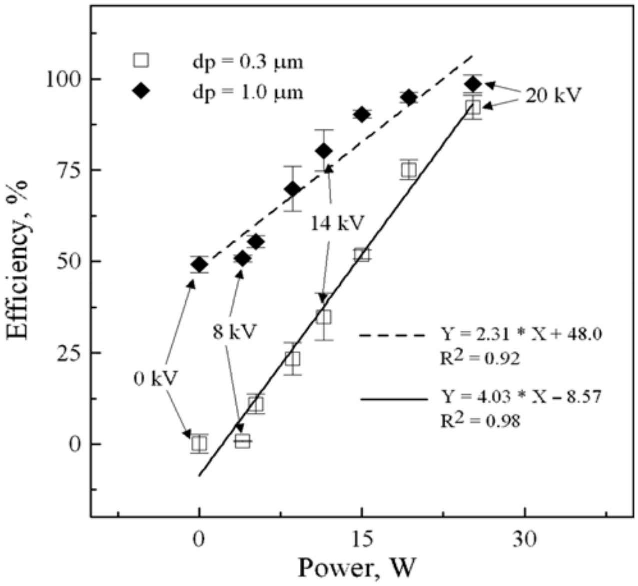

Fig. 9. Removal efficiency of packed dielectric barrier discharge system as a function of required power for various discharge voltages at operating frequency of 60 Hz.

because the discharge voltage should exceed a critical value of 12 kV. Fig. 8 shows a similar conclusion for particles with a diameter of 1.0 μm. The particle removal efficiency increased from 69.8% to 96.1% as the input power was increased from 8.6 W to 39.4 W at a discharge voltage of 12 kV. The gradients of the linear regression were 0.207, 0.269 and 0.856 at discharge voltages of 8 kV, 10 kV and 12 kV, which values were lower than those obtained with a particle diameter of 0.3 μm, because larger particles have a greater electrical mobility and are more easily collected by the glass beads than the smaller particles by the packed dielectric barrier discharge system.

4. Effect of Discharge Voltage on Power Required

Low energy consumption and high particle removal efficiency are important qualities of operating the packed dielectric barrier discharge system. Fig. 9 plots the particle removal efficiency of the packed dielectric barrier discharge system versus the power required at various discharge voltages at an operating frequency of 60 Hz. The results reveal that the removal efficiency increased with the required power, as the discharge voltage was adjusted. As the required power was increased from 4 W to 25.2 W, the particle removal efficiency increased from 0.9% to 92.2% and from 50.7% to 98.6% for particle diameters of 0.3 μm and 1.0 μm, respectively. The gradients of the linear regression were 4.03 and 2.31 for all of the discharge voltages at particle diameters of 0.3 μm and 1.0 μm. The required power of the packed dielectric barrier discharge system by adjusting the discharge voltage was less than that by adjusting the operating frequency at the particular removal efficiency. For 0.3 μm particles, the power required to yield particle removal efficiency >90% by adjusting the discharge voltage was 25.2 W, while that required by adjusting the operating frequency was 39.4 W (Fig. 7). Furthermore, the gradient of the regression of a change in discharge voltage exceeded that of a change in operating frequency, suggesting that the packed dielectric barrier discharge system that is based on adjusting the discharge voltage more effectively and economically removes particulate matters than that is based on adjusting the operating frequency.

CONCLUSIONS

The particle removal efficiency of a dielectric barrier discharge packed with glass pellets was determined at various discharge voltages and operating frequencies. Concentrations of the particulate matter were measured at the inlet and the outlet of the packed dielectric barrier discharge system by using an optical particle counter to determine the particle removal efficiency. The results reveal that the particulate matter in the air stream can be removed efficiently by using a packed dielectric barrier discharge system. The particle removal efficiency of the packed dielectric barrier discharge system with a high discharge voltage exceeded that obtained without a discharge voltage. The particle removal efficiency increased with the discharge voltage. However, the packed dielectric barrier discharge system was ineffective in removing the particulate matter at a low discharge voltage of 8 kV. Under this condition, even as the operating frequency was increased, the particle removal efficiency did not increase. At a discharge voltage of 12 kV, the particle removal efficiency increased from 23.5% to 91.2% for 0.3 μm particles as the operating frequency was increased from 60 Hz to 150 Hz. The effect of the required power on the efficiency of removal of particles by the packed dielectric barrier discharge system was also examined at various operating frequencies and discharge voltages. An increase in input power results in an increase in the removal efficiency of the particulate matter by the packed dielectric barrier discharge system. Moreover, the packed dielectric barrier discharge system based on changing the discharge voltage more economically removes the particulate matter from the air stream than does the system based on a change in operating frequency.

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