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Particulate Matter Removal from a Gas Stream using High-Voltage Discharge Plasma

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Particulate Matter Removal from a Gas Stream using High-Voltage Discharge Plasma

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Abstract: This investigation examines the use of a high-voltage discharge plasma technology to remove particulate matter from an air stream. Concentrations of the particulate matter were measured at the inlet and the outlet of the discharge plasma with the help of an optical particle counter to determine the particle removal efficiency. The experimental results indicate that the particle removal efficiency of the discharge plasma increased with the discharge voltage. The particle removal efficiency rose as high as 93.1% for 0.3 μm particles as the discharge voltage was increased to 20 kV at an operating frequency of 60 Hz. The influence of the operating frequency on the particle removal efficiency was neglected at discharge voltages of 8 kV and 10 kV when the operating frequencies ranged from 60 Hz to 180 Hz. Furthermore, the particle removal efficiency increased with the reflected power when the discharge voltage was varied. A non-linear multivariable regression model was fitted to the experimental data. The good fit of the regression model makes it possible to estimate the particle removal efficiency of the high-voltage discharge plasma.

Keywords: Particulate matter, plasma, particle removal efficiency

INTRODUCTION

High-voltage discharge plasma technology has been considered for use in air pollution control systems for removing mixed air pollutants (1, 2). The plasma

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technology generates free electrons to produce free radicals, ions, and metastables in a reaction zone by using high-voltage discharge. These products are all chemically active and promote the destruction of toxic molecules. Accordingly, the high-voltage discharge plasma technology can be applied to remove undesired species from an air stream in environmental applications, such as sulfur oxides, nitrogen oxides and volatile organic compounds (3–9). Plasma methods have also been investigated for their ability to remove particulate matter from diesel exhaust (10–12). Dan et al. (10) demonstrated that the removal of particulate matter from the diesel exhaust using the non-thermal plasma technique ranged from 25 to 57%. Chae (11) studied the application of a non-thermal plasma approach to treat diesel exhaust. The results revealed that the non-thermal plasma affects the oxidation of particulate matter in diesel exhaust at low temperature. Yao et al. (12) pointed out that the particulate matter from diesel engines could be removed using uneven dielectric barrier discharge reactors. The maximum proportion 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 was increased by decreasing the gap distance of the dielectric barrier discharge reactor.

Recently, human exposure to indoor particulate matter has attracted considerable attention (13, 14). Electrostatic precipitation is one of the commercial devices for removing particulate matter from indoor air. Except the particulate matter removal mechanism, an advanced indoor air cleaning system requires bacterial, odor and VOC control instrument. In some cases, the discharge plasma can act as a combined electrostatic precipitation, UV source, and chemical decomposition reactor for the treatment of mixed air pollutants (15). Particulate matter can be effectively removed using the discharge plasma in indoor environments is worthwhile to know.

This work attempts to experimentally investigate the removal efficiency of particulate matter from gas streams by discharge plasma at various discharge voltages. The influence of the operating frequency on the removal efficiency of the particulate matters was also studied for various particle diameters and discharge voltages. Additionally, the relationship between the reflected power and the particle removal efficiency of the discharge plasma was investigated at various discharge voltages and operating frequencies. Finally, a linear multivariable regression was performed by fitting the experimental data using the least square estimate technique.

EXPERIMENTAL METHODS

This study experimentally determines the particle removal efficiency of discharge plasma at various discharge voltages and operating frequencies. A schematic diagram of the experimental system is illustrated in Fig. 1. The discharge plasma was composed of a Pyrex-glass tube with the diameter of

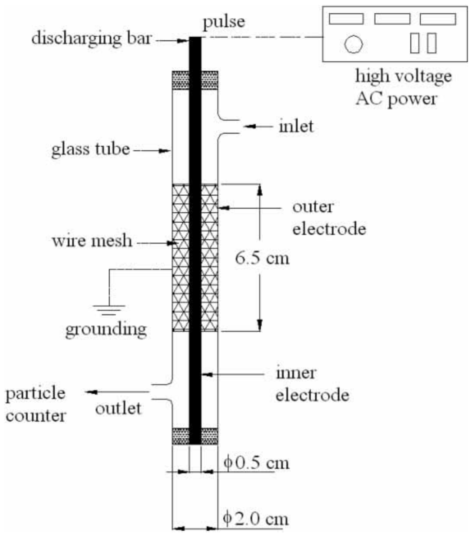

Figure 1. Schematic diagram of high-voltage discharge plasma.

2.0 cm and a stainless steel wire of 0.5 cm diameter that was suspended along the axis of the tube and served as an inner electrode. The grounded 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 ranged from 60 to 180 Hz and adjustable amplitudes ranged from 8 to 20 kV were applied to the inner electrodes to generate plasma to test the removal efficiency of particulate matter from an air stream.

An optical particle counter (LASAIR II, Particle Measuring Systems Inc., Boulder, Colorado, USA) was adopted to measure the particle number concentrations at the inlet and the outlet of the high-voltage discharge plasma to determine the removal efficiency of the particulate matter. LASAIR II is a portable, durable, and lightweight aerosol counter, which measures particle sizes in the range of 0.3 to 25.0 μm with 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 it was scattered from the particulate matter in the air stream of the chamber. The scattered light was picked up by a collecting photo detector and converted to a voltage pulse corresponding to the size of the particles. The inlet particle concentration was measured by the LASAIR II from the air stream, while the outlet particle concentration was measured after they passed through the discharge plasma. The sample flow in the discharge plasma was fixed at 28.3 L/min. The duration of each sampling was maintained at 30 s, and a wait 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 check the constancy of particle concentration. The steadiness of the particle concentration was found to be fewer than 4.8%. One data point at a particular test condition for a particle size was the average of three measurements. The particle removal efficiency, E(%), of the high-voltage discharge plasma can be calculated as:

$$E, \% = 100 \times \left(1 - \frac{C_2}{C_1}\right) \tag{1}$$

where C_1 and C_2 is the number concentration of particulate matter before and after passing through the high-voltage discharge plasma, respectively.

The particle size distributions were measured using multi-stage micro-orifice uniform deposit impactors (MOUDI, Model 100, MSP Corp.). The MOUDI has ten different stages with varying 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 used Teflon filters as substrates and the flow rate was around 30 L/min. A Chemcomb Cartridge (Model 3500, Rupprecht & Patashnick Co., Inc. NY, USA) sampler was adopted to determine the mass concentration of PM_{10} which is particulate matter with an aerodynamic diameter of under 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 work, 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 adopted over 24 hours. The samples of the MOUDI and the Chemcomb Cartridge sampler were pre- and post-weighed using a microbalance (Mettler Toledo Inc, Greifensee, Switzerland) after 24 hours of equilibration at $23 \pm 3^{\circ}C$ and a relative humidity of $40 \pm 5\%$. During the tests, the ambient temperatures ranged from 25.2°C to 30.4°C, and the ambient RH ranged from 60.8% to 71.6%.

RESULTS AND DISCUSSION

Figure 2 plots the particle removal efficiency of the high-voltage discharge plasma against particle diameter for various discharge voltages at an operating frequency of 60 Hz. In this investigation, the distribution of particle sizes was bimodal and the PM_{10} mass concentration ranged from 79 to 86 $\mu g/m^3$. The mass median diameter and the geometric standard deviation of the fine particles were measured to be $0.35 \sim 0.42$ μm and $1.21 \sim 1.29$, while those of the coarse particles were $3.7 \sim 4.2$ μm and $1.49 \sim 1.53$, respectively. The results show that the particle removal efficiency increased with the discharge voltage for various particle diameters. For example, the particle removal efficiency increased from 19.1% to 77.8%

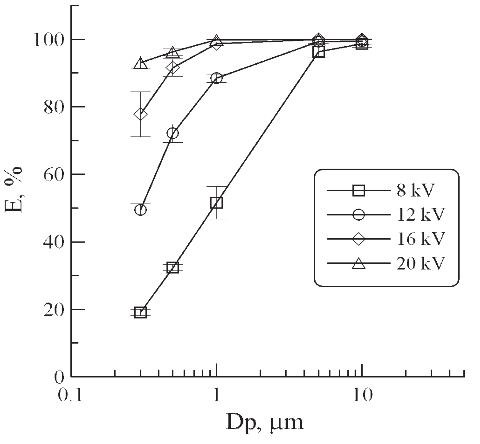

Figure 2. Removal efficiency of discharge plasma as a function of particle diameter at different discharge voltages.

when the discharge voltage increased from 8 kV to 16 kV for a particle diameter of 0.3 μm, while it increased from 51.6% to 98.6% for 1.0 μm particles. As the discharge voltage was increased to 20 kV, the particle removal efficiency increased as high as 93.1% and 99.9% for 0.3 μm and 1.0 μm particles, respectively. It is because an increase in the discharge voltage of the discharge plasma caused a higher ionic wind, and promoted the attraction of particles by the glass tube. Consequently, a higher discharge voltage more easily removes the particles than those by a lower discharge voltage. The results also reveal 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 (16). The particle removal efficiency of the high-voltage discharge plasma can be further expressed as the following equation by assuming well-mixed flow (17):

$$\mathrm{E}, \% = 100 \times [1 - \exp(-\mathrm{hZ})] \tag{2}$$

where h is a constant depending on the flow characteristics, and the electrical mobility, Z, is:

$$\mathrm{Z} \approx \mathrm{C(Dp)}\frac{\mathrm{n(Dp)}}{\mathrm{Dp}} \tag{3}$$

where Dp presents the particle diameter; C(Dp) is the Cunningham correction factor, which can be approximated as $3.69(\lambda/\mathrm{Dp})^{1/2}$ (λ is the mean free path of air molecules) (18), and n(Dp) is the average number of elementary charges of a particle. For the particles larger than about 0.2 μm in diameter, the field charging was the dominant mechanism and n(Dp) was proportional to Dp^2 (19). Therefore, for the particle larger than 0.2 μm in diameter, Z was proportional to $Dp^{1/2}$ and the particle removal efficiency of the high-voltage discharge plasma increased with the particle diameter. In addition, the higher particle removal efficiencies can be found for the higher discharge voltages because of the higher particle charging in the high-voltage discharge plasma.

Figure 3 plots the influence of the operating frequency on the particle removal efficiency of the discharge plasma with a discharge voltage of 12 kV. The figure indicates that the particle removal efficiency increased with the operating frequency for various particle diameters. The particle removal efficiency enhanced from 49.5% to 73.9% for 0.3 μm particles and from 88.4% to 95.5% for 1.0 μm particles as the operating frequency increased from 60 Hz to 120 Hz. The results indicate that increasing the operating frequency effectively improved the particle removal efficiency at a discharge voltage of 12 kV. It is due to the probability of collision between the particles and the glass tube increased in the discharge plasma, increasing the deposition rate of the particulate matter (12). However, the particle removal efficiencies at operating frequencies of 120 Hz, 150 Hz, and 180 Hz were close to each other. This may be attributed to that operating frequencies of 150 Hz and 180 Hz were ineffective for eliminating particulate matter from air streams at a discharge voltage of 12 kV. Figures 4 and 5 present similar results, and reveal that the particle removal efficiencies at operating frequencies of 60 Hz, 120 Hz, 150 Hz, and 180 Hz were close to each other at discharge voltages of 8 kV and 10 kV, respectively. This result follows from that fact that discharge voltages of 8 kV and 10 kV were ineffective for removing particulate matter from the air stream at various operating frequencies. On the contrary, the particle removal efficiency of the discharge plasma was improved using 12 kV discharge voltage at

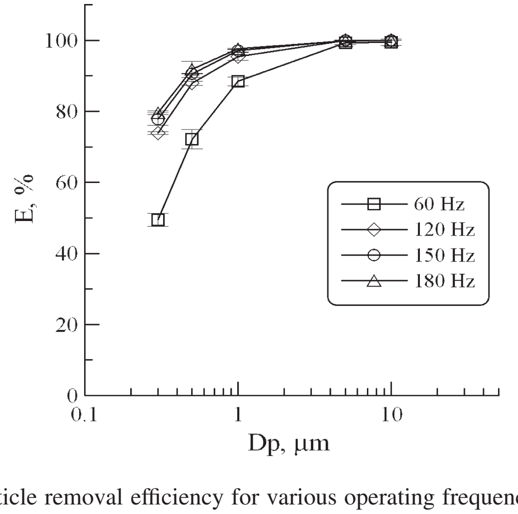

Figure 3. Particle removal efficiency for various operating frequencies at discharge voltage of 12 kV.

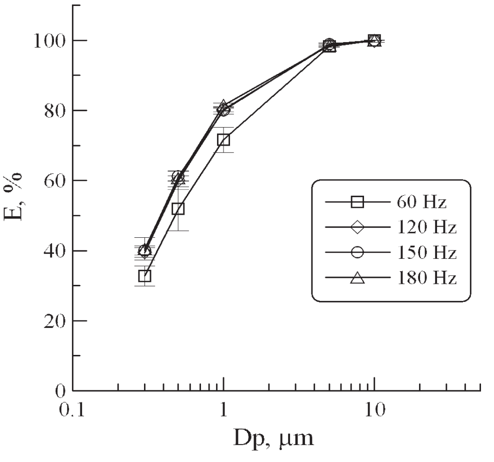

Figure 4. Particle removal efficiency for various operating frequencies at discharge voltage of 10 kV.

operating frequency of 120 Hz. The results demonstrate that the discharge voltage of the discharge plasma dominated the removal efficiency of the particulate matter.

The reflected power of the discharge plasma for removing particulate matter at various operating frequencies (60 Hz, 120 Hz, 150 Hz, and 180 Hz) and various discharge voltages (8 kV, 10 kV, and 12 kV) was shown in Fig. 6 (particle diameter = 0.3 μm) and Fig. 7 (particle diameter = 1.0 μm). Figure 6 reveals that the reflected power of the

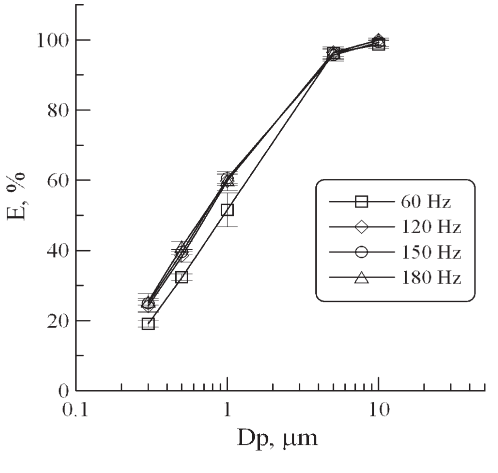

Figure 5. Particle removal efficiency for various operating frequencies at discharge voltage of 8 kV.

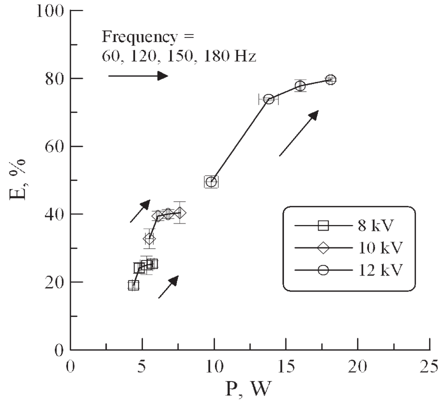

Figure 6. Reflected power of discharge plasma for various discharge voltages and operating frequencies at particle diameter of 0.3 μm.

discharge plasma increased as the particle removal efficiency was improved at a 12 kV discharge voltage. This result indicates that the particle removal efficiency increased with the operating frequency and an increasing reflected power was observed at a discharge voltage of 12 kV. The increase in the reflected power was posited to be one of the reasons of the effectiveness of the removal of particles by the discharge plasma. 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 (10, 12). The particle removal efficiency was unapparently raised with the operating frequency at discharge voltages of 8 kV and 10 kV, but it did at a discharge

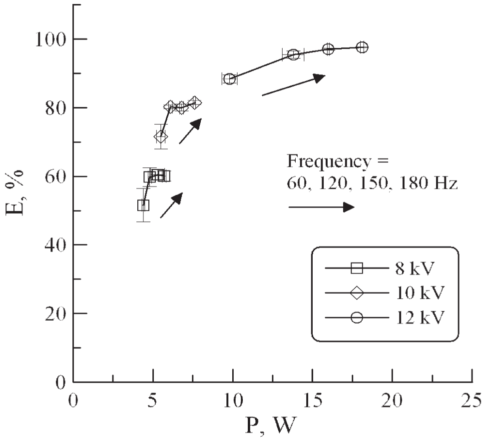

Figure 7. Reflected power of discharge plasma for various discharge voltages and operating frequencies at particle diameter of 1.0 μm.

voltage of 12 kV. For example, the particle removal efficiency increased only from 19.1% to 25.4% and from 32.8% to 40.5%, whereas the reflected power was increased from 4.4 W to 5.7 W and from 5.5 W to 7.6 W at discharge voltages of 8 kV and 10 kV, respectively. A similar conclusion can be found in Fig. 7 for particles with a diameter of 1.0 μm. The results reveal that the particle removal efficiency increased from 88.4% to 97.7% as the reflected power was increased from 9.8 W to 18.1 W at a discharge voltage of 12 kV.

Figure 8 plots the particle removal efficiency of the discharge plasma versus the reflected power at various discharge voltages at an operating frequency of 60 Hz. The results reveal that the removal efficiency increased with the reflected power, as the discharge voltage was varied. As the reflected power was increased from 4.4 W to 28.4 W, the particle removal efficiency increased from 19.1% to 93.1% and from 51.6% to 99.9% for particle diameters of 0.3 μm and 1.0 μm, respectively. For 0.3 μm particles, the reflected power to yield particle removal efficiency of 79.6% by adjusting the operating frequency was 18.1 W (Fig. 6). It demonstrates that the discharge plasma that involves changing the discharge voltage more effectively removes particulate matters than that involves changing the operating frequency.

A non-linear multivariable regression was performed to assist in the interpretation of the obtained experimental data for the various discharge voltages and operating frequencies. The particle removal efficiency, E(%), was assumed to vary in exponential relationships with the reflected power (20) and it can be expressed as

$$E, \% = 100 - \exp\left[-kDp^{a} \left(\frac{Pw}{Q} \right)^{b} \right] \tag{4}$$

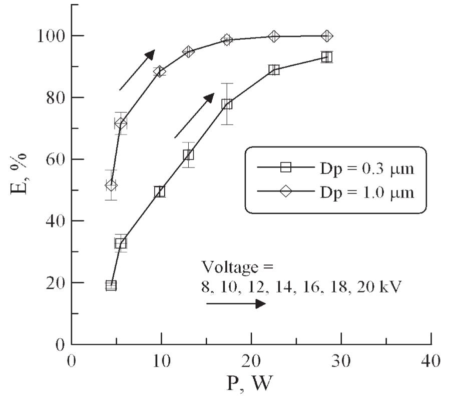

Figure 8. Removal efficiency of discharge plasma as a function of required power for various discharge voltages at operating frequency of 60 Hz.

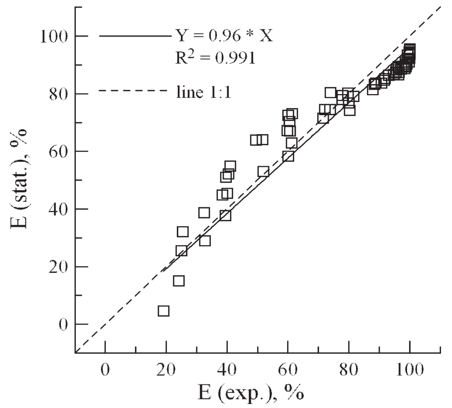

Figure 9. Comparison of experimental removal efficiency with statistical removal efficiency of discharge plasma.

where Pw is the reflected power (W); Q is the flow rate (L/min); and k, a, and b is the constant.

The regression analysis was conducted by fitting the equation to the experimental data using the least square estimate technique. The results from the non-linear multivariable regression are given by equation (5).

$$E, \% = 100 - \exp\left[2.05Dp^{-0.2}\left(\frac{Pw}{Q}\right)^{-0.3}\right] \tag{5}$$

In Fig. 9 we show that the particle removal efficiency obtained from the statistical regression plotted against those measured by the experiment using the high-voltage discharge plasma. The results reveal that the particle removal efficiency determined by the statistical regression are highly correlated with those obtained experimentally ($R^2 = 0.991$) for the discharge voltage $= 8 \sim 20$ kV, the operating frequency $= 60 \sim 180$ Hz, the particle diameter $= 0.3 \sim 5$ μm, the reflected power $= 4.4 \sim 28.4$ W and the flow rate $= 28.3$ L/min. The mean ratios of statistical and experimental removal efficiency are close to 1, indicating the values are in agreement. Thus, the particle removal efficiency of the high-voltage discharge plasma can be possible predicted using the developed statistical regressions. The parameters proposed herein can be easily used in operating the high-voltage discharge plasma.

CONCLUSIONS

In this work, the particle removal efficiency of a high-voltage discharge plasma technology was determined at various discharge voltages and operating frequencies. The results demonstrate that the particle removal efficiency of the discharge plasma increased with the discharge voltage. The particulate matter in the air stream can be removed efficiently at a discharge voltage of 20 kV. However, the discharge plasma was ineffective for removing particles at the discharge voltages of 8 kV and 10 kV when the operating frequencies ranged from 60 Hz to 180 Hz. Under this condition, the particle removal efficiency did not increase with the operating frequency. The influence of the reflected power on the particle removal efficiency was also studied at various operating frequencies and discharge voltages. An increase in reflected power leads to an increase in the particle removal efficiency by the discharge plasma. Additionally, a non-linear multivariable regression model was proposed by a good fit to the experimental data. The approach presented in this paper will be useful for removing the particulate matter from the air stream and estimating the particle removal efficiency of the high-voltage discharge plasma.

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REFERENCES

1. Chang, J.S., Lawless, P.A., and Yamamoto, T. (1991) Corona discharge processes. *IEEE Trans. Plasma Sci.*, 19: 1152–1166.
2. Urashima, K. and Chang, J.S. (2000) Removal of volatile organic compounds from airstreams and industrial flue gases by non-thermal plasma technology. *IEEE Trans. Dielec. Electrical Insul.*, 7: 602–614.
3. Kim, H., Han, J., Kawaguchi, I., and Minami, W. (2007) Simultaneous removal of NO_x and SO_2 by a nonthermal plasma hybrid reactor. *Energ. Fuel.*, 21: 141–144.
4. Dhali, S.K. and Sardja, I. (1991) Dielectric-barrier discharge for processing of SO_2/NO_x. *J. Appl. Phys.*, 69: 6319–6324.
5. Sun, W., Pashaie, B., Dhali, S.K., and Honea, F.I. (1996) Non-thermal plasma remediation of SO_2/NO using a dielectric-barrier discharge. *J. Appl. Phys.*, 79: 3438–3444.
6. Riahi-Nezhad, C.K., Tsouris, C., DePaoli, D.W., and de Almeida, V.F. (2005) Removal of micron-size droplets from an air stream by means of electric fields. *Sep. Sci. Technol.*, 40: 367–381.
7. Un, U.T., Koparal, A.S., and Ogutveren, U.B. (2007) Sulfur dioxide removal from flue gases by electrochemical absorption. *Sep. Purif. Technol.*, 53: 57–63.
8. Wallis, A.E., Whitehead, J.C., and Zhang, K. (2007) The removal of dichloromethane from atmospheric pressure air streams using plasma-assisted catalysis. *Appl. Catal. B: Environ.*, 72: 282–288.
9. Rezchikov, V.G. and Kuznetsova, T.S. (2007) Removal of carbon-containing impurities from hydrogen using an electrical discharge. *Inorg. Mater.*, 43: 18–19.

10. Dan, Y., Dengshan, G., Gang, Y., Xianglin, S., and Fan, G. (2005) An investigation of the treatment of particulate matter from gasoline engine exhaust using non-thermal plasma. *J. Hazard Mat.*, B127: 149–155.
11. Chae, J.O. (2003) Non-thermal plasma for diesel exhaust treatment. *J. Electrostat.*, 57: 251–262.
12. Yao, S., Fushimi, C., Madokoro, L., and Yamada, K. (2006) Uneven dielectric barrier discharge reactors for diesel particulate matter removal. *Plasma Chem. Plasma Process*, 26: 481–493.
13. Li, Y. and Chen, Z. (2003) A balance-point method for assessing the effect of natural ventilation on indoor particle concentrations. *Atmos. Environ.*, 37: 4277–4285.
14. Lee, B.U., Yermakov, M., and Grinshpun, S.A. (2004) Removal of fine and ultrafine particles from indoor air environments by the unipolar ion emission. *Atmos. Environ.*, 38: 4815–4823.
15. Chang, J.S. (2001) Recent development of plasma pollution control technology: a critical review. *Sci. Technol. Adv. Mater.*, 2: 571–576.
16. Mizuno, A. (2000) Electrostatic precipitation. *IEEE Trans. Dielec. Electrical. Insul.*, 7: 615–624.
17. Byeon, J.H., Hwang, J., Park, J.H., Yoon, K.Y., Ko, B.J., Kang, S.H., and Ji, J.H. (2006) Collection of submicron particles by an electrostatic precipitator using a dielectric barrier discharge. *J. Aerosol Sci.*, 37: 1618–1628.
18. Lee, K.W. and Liu, B.Y.H. (1980) On the minimum efficiency and the most penetrating particle size for fibrous filters. *Journal of the Air Pollution Control Association.*, 30: 377–381.
19. Cardello, N., Volckens, J., Tolocka, M.P., Wiener, R., and Buckley, J. (2002) Performance of a personal electrostatic precipitator particle sampler. *Aerosol Sci. Technol.*, 36: 162–16520.
20. Cooper, C.D. and Alley, F.C. (2002) *Air Pollution Control*; Waveland Press: Illinois.