行政院國家科學委員會專題研究計畫成果報告

室內空氣清淨機效能測試改良與研發

Study on the Performance Characteristics of Indoor Air Cleaners

計畫編號：NSC 88-2314-B-002-144

執行期限：87 年 8 月 1 日至 88 年 10 月 31 日

主持人：陳志傑　　國立台灣大學公共衛生學院

一、Abstract

This study investigates the filtration characteristics of a miniature dual saw-like electrodes electrostatic precipitator (ESP). Parameters such as particle size, rate of airflow through the ESP, voltage of the charge electrode, and discharge polarity were included to study their influence on aerosol penetration through the ESP. Polydispersed and monodispersed particles ranged from 30 nm to 10 μm were used as the challenge aerosols.

Experimental results indicated that the aerosol penetration through the ESP decreased (from 96 % to 15 % for 0.3 μm) as the voltage of the discharge electrode increased (from +4 kV to +8 kV) at a flow rate of 30 L/min. At a fixed electrode voltage (+8 kV), aerosol penetration increased from 15 % to 69 % for 0.3 μm particles as the flow rate increased from 30 L/min to 120 L/min. The most penetrating particle size was in the range of 0.25 μm to 0.5 μm depending on the discharge voltage and the flow rate. In general, the most penetrating particle size of the ESP tested was found to become smaller as a decrease in the discharge voltage and/or an increase in the testing flow rate. At the same voltage level but opposite polarity, the aerosol penetration through the ESP with negative corona was lower than that with positive corona. The difference in aerosol penetration was a factor of about 2 between the negative and positive coronas for 0.3 μm particles and this difference was independent of the discharge voltage. Regarding energy conservation, using a negative-polarity ESP was more economical if the same efficiency was required. However, the ozone generated by the ESP with negative polarity was about five times greater than that generated with positive polarity. Therefore, when using an ESP as an indoor air cleaner, a positive corona should be used to limit ozone production.

Key words: electrostatic precipitator, particle size, ozone

中文摘要

本研究的目的在於藉著評估一小型靜電集塵器之過濾特性，以瞭解不同粒徑微粒、流量、電場強度以及放電極電性等因素如何影響靜電集塵器之收集效率。至於研究中所使用的測試微粒則包括多粒徑以及單一粒徑兩種分佈，其粒徑範圍則約為 30 nm 至 10 μm。實驗中亦同時監測不同條件下所產生的臭氧濃度。

結果顯示，此小型靜電集塵器之氣懸微粒貫穿率隨操作電壓的增加而降低，以 0.3 μm 為例，在流量 30 L/min 下，當操作電壓為+4 kV 時，其微粒貫穿率為 96 %，而當電壓提昇至+8 kV 時，貫穿率則降至 15 %。若電壓固定為+8 kV，則當氣流量由 30 L/min 增加至 120 L/min 時，0.3 μm 微粒的貫穿率約提高 54 %。至於其最易穿透粒徑約在 0.25 至 0.5 μm 之間，並隨不同的流量、電壓而有所不同。一般而言，最易穿透粒徑隨操作電壓的減小以及測試流量的增加而往小粒徑方向移動。另外，在任意相同電壓但不同電性的條件下，以 0.3 μm 微粒而言，正電暈之靜電集塵器的微粒貫穿率約為負電暈的兩倍，因此就節約能源的觀點，負電暈相對於正電暈是較為經濟的。然而在臭氧的產生量方面，於相同電場強度之下，負電暈所產生的臭氧濃度則為正電暈的 5 倍。

關鍵詞：靜電集塵器、微粒粒徑、臭氧

二、Introduction

As widely viewed in recent decades, human exposure to indoor air pollutants has increased due to a variety of factors, including the construction of more tightly sealed buildings, the reduction of ventilation levels to save energy, the use of synthetic building materials and furnishings, and the use of formulated personal care products, pesticides, and household cleaners. Moreover, studies from the United States and Europe show that most people spend as much as 90 % of their time indoor [1]. Consequently, increased attention is paid to the human health implication of particles that are found indoors. Therefore, more and more indoor air cleaning devices are used to improve indoor air quality.

Air cleaners can be categorized according to the method they employ for removing particles from the air. Mechanical filters may be installed in ducts in homes with central heating and/ or air-conditioning or may be used in portable devices, which contain a fan to force air through the filter. Electronic air cleaners as well as electrostatic precipitators, use an electrical field to trap charged particles. Hybrid units, combining these two removal methods are also available.

Electrostatic precipitators (ESPs) are one of the most commonly used devices to control particle emissions from many industrial processes. The basic principles of their operation are relatively straightforward, and are well described in previous literature [2, 3]. As a class ESPs are characterized by low-pressure drop, higher collection efficiency for small particles, the ability to handle high dust concentrations, comparatively low maintenance costs, and the allowing of a wider temperature range [4, 5]. For these reasons, electronic air cleaners perhaps should be the most widely used indoor air-cleaning devices. However, there are no comprehensive requirements regulating the performances of these products.

The first mathematical model of ESP performance was the Deutsch-Anderson model [6]. Generally speaking, the gas flow used in industry is turbulent, and the above model can be used to predict the grade collection efficiency for these industrial ESPs [7]. Since the pioneering work mentioned above, a considerable amount of research on more accurate models has been done. These models can range in complexity from single equation type models [7], in which the electrostatic precipitation trends are easy to anticipate, to large computer models [8. 9]. Although many of these models for predicting the total collection efficiency of ESPs give excellent results, they can be used only for special applications/ or assumptions. Moreover, these models' methods of calculating the electric field strength distribution of an ESP are generally available only for wire-tube and wire-flat plate geometry. Various new types of discharge electrodes and collecting electrodes have been increasingly applied. Although researchers have studied the electric field strength distributions for these new discharge electrode designs [10], this model might still not be used extensively. Meanwhile, conducting an experiment becomes the only way to know the exact performance of a newly designed ESP, especially for miniature electronic indoor air cleaners.

Although the performance of an ESP has been studied for about a century, only two experimental studies [5. 11] showed the ESP collection efficiency as a function of particle size. Meanwhile, for small-scale electronic indoor air cleaners, no experimental data has yet provided this information. Many of the discussions focused on the overall mass efficiency, which is insufficient to clearly represent the collection of fine particles. Furthermore, knowing the most penetrating particle size of an ESP is an important consideration in applying the ESP and in setting performance testing requirements.

While there is now a good understanding of what happens in a precipitator, and of the important parameters, finding good quantitative models based on laboratory scale experiments that are also applicable to full scale industrial units is relatively difficult. A great deal of basic and applied research is necessary before electrostatic precipitators can be fully understood and quantified.

This study investigates the performance of a miniature dual saw-like electrodes ESP by examining its collection efficiency as well as how the most penetrating particle size be affected by parameters such as particle size, rate of air flow through the ESP, and the polarity and voltage of the discharge electrode.

Ozone generation due to corona discharge is an important problem in using an EPS as an indoor air cleaner. Ozone is a strong oxidant that, when inhaled, can react with the tissues of the inhalation route and cause problems such as shortness of breath, chest pain, coughing and severe respiratory discomfort [12]. Exposure to ozone may also result in lung cancer [13, 14]. Thus, this study also investigates the ozone concentration generated by the positive and negative coronas at different voltages.

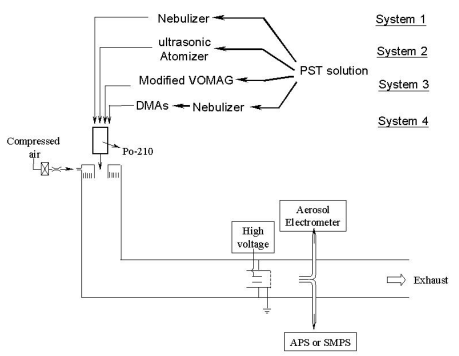

Fig 1. Schematic diagram of the experimental set-up.

三、Experimental materials and methods

To conduct the miniature ESP performance test, aerosol particles with different sizes and distributions were generated by four aerosol generation systems, as shown in figure 1. A constant output atomizer (model 3076, TSI Inc., St. Paul, Minn.) and an ultrasonic atomizing nozzle (model 8700-120, Sonotek Inc., Highland, N.Y.) were used to generate polydisperse submicrometer-sized and micrometer-sized aerosol particles, respectively. In order to avoid the particle charge effect, the particles were then passed through a 22.5-mCi Po-210 radioactive source (model P-2001, NRD Inc.) to neutralize the aerosol particles to the Boltzmann charge equilibrium.

To investigate the particle charges given by the ESP, a vibrating orifice monodisperse aerosol generator (VOMAG, model 3050, TSI, Inc.) was modified to generate monodisperse PST particles with aerodynamic diameters ranging from 1.24 μm to 8.35 μm. Two electrostatic classifiers in series were used to generate monodisperse submicrometer-sized challenge aerosol. Potassium sodium tartrate tetrahydrate, PST, was chosen as the test material.

Two different spectrometers were used to measure the aerosol concentration and size distribution: a scanning mobility particle sizer (SMPS, model 3934U, TSI Inc.) for particles smaller than 0.7 μm, and an aerodynamic particle sizer (APS, model 3320, TSI Inc.) for particles larger than 0.7 μm.

The total aerosol charge was measured with an aerosol electrometer (model 3068, TSI, Inc.). The per particle charge was then calculated using the particle number concentration measured by the APS and SMPS, respectively. Aluminum foil was glued to the inner surface of the chamber and grounded to minimize the loss of particles due to electrostatic attraction force.

Testing flows ranged from 30 to 120 L/min to study flow dependency. All air flows were controlled and monitored by mass flow controllers (Hastings Instruments, Hampton, VA).

The ozone generated by the ESP was sampled 20 cm downstream of the ESP exit and measured with an ozone analyzer (model 400, API Inc.).

During testing, the original power supply was replaced with a reversible polarity, direct-current high voltage power supply (model SL50PN300, SPELLMAN High Voltage Electronics Corporation). This power supply made it possible to measure the voltage-current characteristics and ozone production of the ESP operated both with positive and negative polarity.

四、Results and Discussion

Fig. 2 plots ion currents associated with the positive and negative corona, the current-voltage characteristic curves, against applied voltage. The data were obtained for clean plates in a particle free chamber. Obviously, the negative corona current is larger than the positive corona current for applied voltage with equal but opposite-polarity. In general, the difference between negative and positive corona is a factor of about 3. This is because the mechanism of the negative corona differs intrinsically from that of the positive corona [15]. For the positive corona, the spark-over phenomenon occurred at a voltage of more than 9.6 kV. Meanwhile, for negative corona it occurred at about 12 kV.

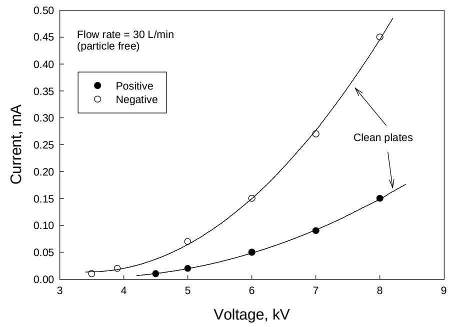

Fig 2. Experimental results on the voltage-current characteristic curves of the ESP.

Fig. 3, which contains the data from two particle spectrometers, the SMPS and APS, shows the experimental results of aerosol penetration through the positive corona ESP at different applied voltages. When tested at the same flow rate, aerosol through the ESP clearly decreased when the applied voltage was increased. For example, the penetration of the 0.3 μm particles decreased from

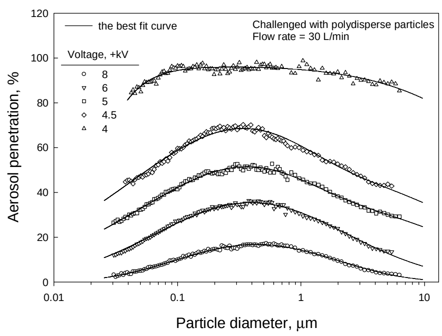

Fig 3. Aerosol penetration through the ESP versus particle size for a flow rate of 30 L/min and different applied voltages. (Using polydisperse particles as challenge aerosol)

96% to 15% as the applied voltage increased from +4 kV to +8 kV. This conflicts with the results reported in a previous study [11] , which showed that the collection efficiencies of the ESP decreased with increasing ion current. However, this phenomenon was not explained in detail in that study. The most penetrating particle size of the ESP also depended on the applied voltage. As the applied voltage decreased, the particle size became smaller. For the testing flow rate of 30 L/min, the most penetrating particle size was 0.5 μm and 0.3 μm for the applied voltages of +8 kV and +4.5 kV, respectively. This result coincides with what normally regarded as the most penetrating size (or collection minimum) of a mechanical filter [16]. The aerosol penetration curves as a function of particle size are also obtainable by using monodisperse particles as the challenge aerosol. Therefore, if the study did not require particle charge information, using polydisperse particles as the challenge aerosol could be a more convenient and efficient way to get the data of penetration curves as a function of particle size.

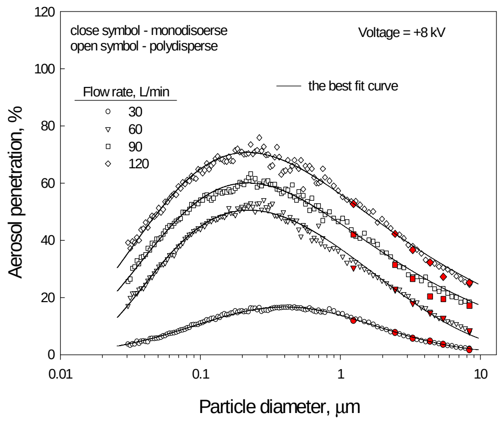

Fig 4. Aerosol penetration through the ESP versus Particle size for an applied voltage of +8kV and different testing flow rates.

Fig. 4 indicates that testing flow rate also significantly affects aerosol penetration through the ESP. In general, the aerosol penetration increases with increasing flow rate, because a lower flow rate allows particles longer retention time to deposit on the collection plates. For example, at the applied voltage of +8kV, the penetration of 0.3 μm particles through the ESP was about 16% and 70% for the testing flow rates of 30 L/min and 120 L/min, respectively. The most penetrating particle size of the ESP decreased with an increasing flow rate. Studies of mechanical filters observed the same phenomenon [17].

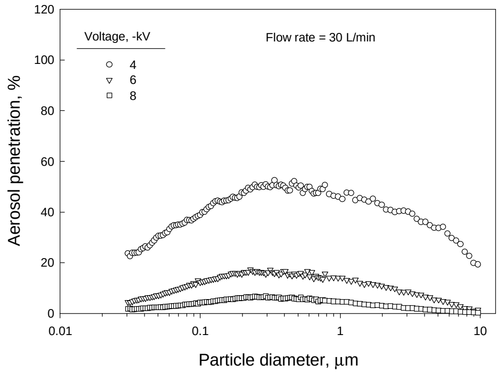

Fig 5. Aerosol penetration through the negative polarity ESP versus Particle size for different applied voltages.

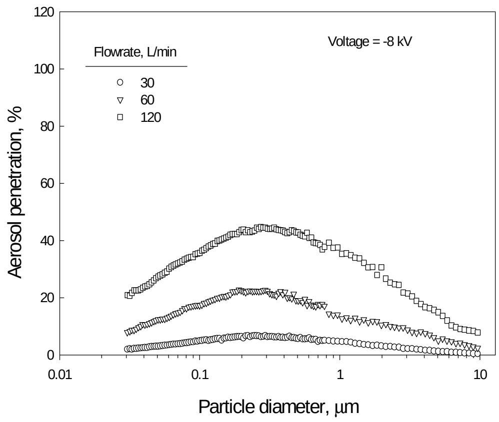

Fig 6. Aerosol penetration through the negative polarity ESP versus Particle size for different testing flow rates.

This study also examined aerosol penetration through negative-polarity ESP of different applied voltages and different testing flow rates, as shown in Figs. 5 and 6, respectively. As in the case of positive-polarity, the aerosol penetration through the ESP increased with decreasing applied voltage and increasing testing flow rate. However, at the same voltage level but opposite polarity, the aerosol penetration through the ESP with negative corona was lower than that with positive corona, as Fig. 7 shows. Regardless of voltage level, for an aerosol size of 0.3 μm, the difference in aerosol penetration between negative and positive corona is a factor of 2 (50% vs. 96% for 4kV; 16% vs. 35% for 6kV; 6% vs. 16% for 8kV). This study also shows that the aerosol penetration curves were almost the same at the voltage level of –6kV and +8kV. In this case, the power level of the negative-polarity ESP was less than that of the positive-polarity one (0.13mA×6kV vs. 0.13mA×8kV). Therefore, to achieve the same efficiency while conserving energy, it is more economical to use a negative-polarity ESP.

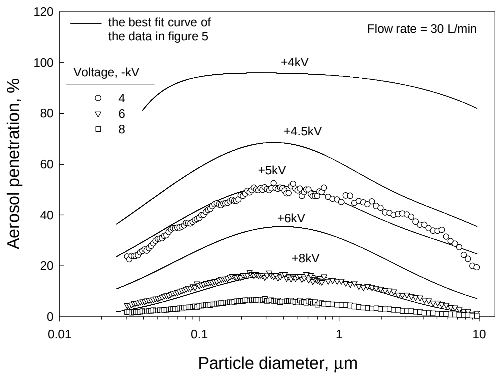

Fig 7. Comparison of aerosol penetration curves between negative and positive corona.

Fig. 8 shows the average particle charge as a function of particle size. This figure reveals that as expected particle charge increased with increasing applied voltage. For submicrometer particles, the number of the particle charge was proportional to the particle diameter at the same voltage level. However, for the micrometer size range, although larger particles had more charges at the same corona voltage, their particle charge was not proportional to

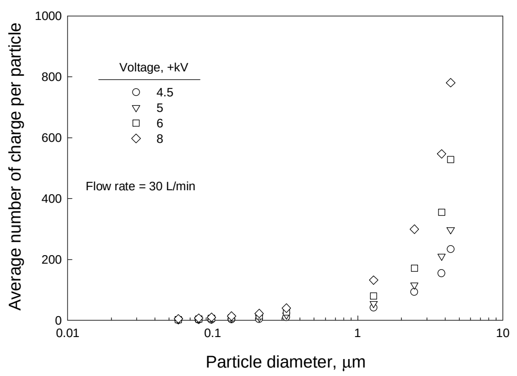

Fig 8. Particle charge versus particle size for different applied voltages.

the square of the particle diameter. It was about an order of 1.6. Moreover, at different testing flow rates, particle charges increased with increasing testing flow rate, which was shown in Fig. 9. Accordingly, it might result from inhomogeneous particle charge, which is caused by an inhomogeneous distribution of electrical strength and masking effect, i.e., particles that have the same size might not get equal charges in the ESP. Therefore, greater numbers of more highly charged particles might penetrate as testing flow rate increased, and would then be counted by the aerosol electrometer. However, this phenomenon certainly needs to be studied further.

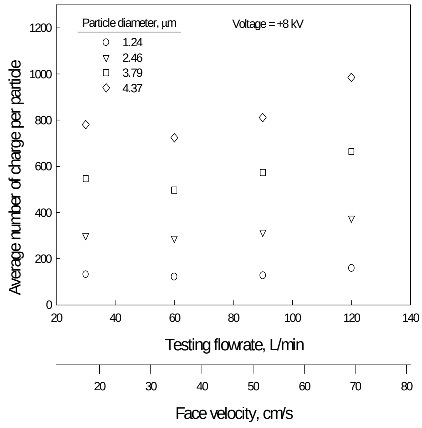

Fig 9. The effect of testing flow rate on particle charges.

A previous study [18] reported that ozone production was linear on the corona current, as shown in Fig. 10. It clearly showed that the ozone generated by the ESP with negative polarity was higher than that generated with positive polarity. Comparing the slope of the linear regression lines in Fig. 10 reveals that the difference was more than five-fold. At an ion current of 0.15 mA, the ozone concentration was 1626 ppb and 272 ppb for the negative and positive polarity, respectively. This finding agrees with a previous study [19] that showed a nearly six-fold difference in ozone generation between negative and positive polarity air cleaners. Therefore, the wires in the ionizing section of an ESP are normally operated with a positive corona discharge to limit ozone production.

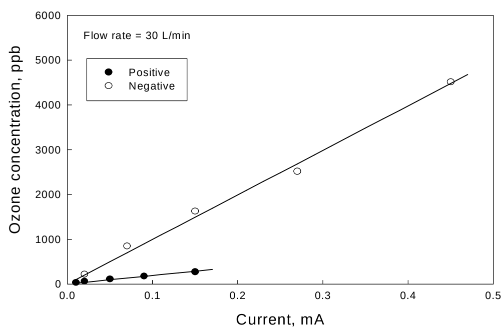

Fig 10. Ozone generation versus ion current for positive and negative polarity of corona.

五、Conclusions

This study investigated the filtration characteristics of a miniature dual saw-like electrodes ESP by considering the influences of particle size, discharge voltage and polarity, and testing flow rate. This experimental approach allowed examination of the particle size with the collection minimun of an ESP, which is an important factor for setting up the test requirements. To maximize the accuracy of the test result, the size of the challenge aerosol should be around the most penetrating size [16].

Experimental results indicated that aerosol penetration through the ESP tested decreased with increasing corona voltage and decreasing flow rate through the ESP. The penetration was highly dependent on particle size. The most penetrating particle size of the ESP ranged from 0.25 ~ 0.5 μm, depending on corona voltage and flow rate. To achieve the same collection efficiency, it is more economical to use a negative polarity ESP. However, when used in indoor air cleaners, ESPs normally use a positive corona discharge because of lower ozone production.

References

1. U.S. Environmental Protection Agency, Office of Air and Radiation. Report to Congress on Indoor Air Quality, Volume II: Assessment and Control of Indoor Air Pollution, pp. I, 4-14. EPA400-1-89-001C, 1989.
2. White H.J., Electrostatic precipitation of fly ash. J. Air. Poll. Contr. Assoc. 27: 15-21, 114-120, 206-217, 308-318, 1977.
3. McLean, K.J., Electrostatic precipitators. IEE Proceedings, 135(6):347-362, 1988.
4. Hinds, W.C., Aerosol Technology: Electrical Properties, J. Wiley and Sons, New York, p 305, 1982.
5. Chang, C.L., Influences of Design and Operation Parameters on the ESP Efficiency. Ph.D. thesis, Institute of Environmental Engineering, National Chiao Tung University, Taiwan, 1998.
6. Flagan, R.C. and John, H.S., Fundamental of Air Pollution Engineering, Chapters 5 and 7, Prentice Hall Inc., 1988.
7. Zhao, Z.M., and Robert, P., A Semi-Empirical Approach to Predict the Total Collection Efficiency of Electrostatic Precipitators. Chem. Eng. Comm., 148-150: 315-331, 1996.
8. Gooch, J.P. and Francis, N.L., A Theoretically Based Mathematical Model for Calculation of Electrostatic Precipitator Performance. J. Air. Poll. Contr. Assoc. 25(2): 108-113, 1975.
9. Leonard, G., Mitchner, M. and Self, S.A., Particle Transport in Electrostatic Precipitators. Atmos. Environ. 14: 1289-1299, 1980.
10. Hao, J., He, K., and Chao, H., Calculation of Electric Field Strength Distributions for New Electrostatic Precipitator Discharge Electrode Designs. J. Air Waste Manage. Assoc. 40: 1510-1513, 1990.
11. Cheng, Y.S., Yeh, H.C, and Kanapilly, G.M., Collection Efficiencies of a Point-to-plane Electrostatic Precipitator. Am. Ind. Hyg. Assoc. J. 42: 605-610, 1981.
12. American Lung Association (1996). When You Can't Breathe, Nothing Else Matters. From http://www.lungusa.org/noframes/global/news/report/viron/virozonefac.html
13. Reiser, K M., Tyler, W. S., Hennessy, S. M., Dominquez, J. J., and Last, J. A., Long-term Consequences of Exposure to Ozone. Toudcol. Appl. Pharmacol. 89: 314, 1987.
14. Witschi, H., Ozone, Nitrogen Dioxide and Lung Cancer: A Review of Some Recent Issues and Problems. Taricolo. 48:1-20, 1988.
15. Harry, J.W., Resistivity Problems in Electrostatic Precipitation. J. Air Pollut. Control Assoc. 24(40): 314-338, 1974.
16. Chen, C.C., Huang, S.H., Chen, C.W., and Huang, Y.S., Factors Influencing Filter Penetration and Quality. Am. Ind. Hyg. Assoc. J. submitted, 1999.
17. Chen, C.C. and Huang, S.H., The Effects of Particle Charge on the Performance of a Filtering Facepiece. Am. Ind. Hyg. Assoc. J. 59: 227-233, 1998.
18. Hautanen, J.H., Janka, K., Keskinen, J., Lehtimaki, M., and Kivisto, T., Optimization of filtration efficiency and ozone production of the electrostatic precipitator. J. Aerosol Sci. 17(3): 622-626, 1986.
19. Boelter, K.J. and Davidson, J.H., Ozone generation by indoor, electrostatic air cleaners. Aerosol Sci. and Technol. 27(6): 689-708, 1997.