Asian Journal of Atmospheric Environment
Vol. 11, No. 2, pp. 131-137, June 2017
doi: https://doi.org/10.5572/ajae.2017.11.2.131
ISSN (Online) 2287-1160, ISSN (Print) 1976-6912

Technical Information

Improvement of a High-volume Aerosol Particle Sampler for Collecting Submicron Particles through the Combined Use of a Cyclone with a Smoothened Inner Wall and a Circular Cone Attachment

Tomoaki Okuda* **and Ryoma Isobe**

Department of Applied Chemistry, Faculty of Science and Technology, Keio University, 3-14-1 Hiyoshi, Kohoku-ku, Yokohama 223-8522, Japan

*Corresponding author. Tel: +81-45-566-1578, E-mail: okuda@applc.keio.ac.jp

ABSTRACT

A cyclone is an effective tool to facilitate the collection of aerosol particles without using filters, and in cell exposure studies is able to collect a sufficient amount of aerosol particles to evaluate their adverse health effect. In this study, we examined two different methods to improve the aerosol particle collection efficiency of a cyclone. The individual and combined effects of reducing the surface roughness of the inner wall of the cyclone and of using a circular cone attachment were tested. The collection efficiency of particles of diameter 0.2 μm was improved by approximately 10% when using a cyclone with a smoothened inner wall (average roughness $Ra=0.08$ μm) compared with the original cyclone ($Ra=5.1$ μm). A circular cone attachment placed between the bottom section of the cyclone and the top section of a collection bottle, resulted in improved collection of smaller particles without the attachment. The 50% cutoff diameter of the modified cyclone (combined use of smoothened inner wall and attachment) was 0.23 μm compared to 0.28 μm in the original model. The combined use of these two techniques resulted in improved collection efficiency of aerosol particles.

Key words: Circular cone attachment, Collection efficiency, Cyclone, Surface roughness, Fine particles, Ultrafine particles

1. INTRODUCTION

Exposure to atmospheric aerosols is a serious concern for human health (Lelieveld *et al*., 2015; IARC, 2013; OECD, 2012; Pope *et al*., 1995; Dockery *et al*., 1993). A threshold of $PM_{2.5}$ (particulate matter that passes through a size-selective inlet with a 50% efficiency cut-off at an aerodynamic diameter of 2.5 μm) has been promoted in regulation worldwide over the last 10-20 years (USEPA, 2013; Ministry of Environment, Japan, 2009; European Parliament and of the Council, 2008). These regulations were set based on numerous epidemiological studies, many of which have reported adverse health effects of particulate matter. However, the detailed mechanisms of the cellular biochemical reactions associated with the toxicity of particulate matter are not yet well understood. The major reason for this is the difficulty of isolating a sufficient amount of aerosol particles to conduct cell-level toxicity assays (Okuda *et al*., 2015). In general, studies on cell exposure to aerosol particles have been conducted using particulate matter collected by vibrating aerosol-loaded filters (Ogino *et al*., 2014; Lichtveld *et al*., 2005), yet the particles used in such an exposure study may not be the same as those present in ambient air. Possible contamination from the filter material should also be considered (Van Winkle *et al*., 2015). In addition, sample handling to obtain particles for exposure experiments is highly complicated and time consuming. Furthermore, the amount of particles that are collected on a filter is often insufficient to perform exposure studies. The development of techniques that allow researchers to collect a sufficient amount of aerosol particles for exposure studies without the use of filters is therefore required. While previous studies reported that cyclone is an effective means to facilitate the collection of aerosol particles for an exposure study (Ogino *et al*., 2017; Okuda *et al*., 2015; Rule *et al*., 2010), the collection efficiency of cyclones may still be improved.

The surface roughness of a cyclone would plays an important role in the vortex structure that controls cyclone performance. A smoother surface on the inner wall of a cyclone may reduce friction between air and surface, which in turn is related to vortex intensity and pressure drop across the cyclone (Kaya *et al*., 2011; Yoshida *et al*., 1991; Zhou and Soo, 1990). Therefore, superior separation performance may be observed in a cyclone if the inner wall is relatively smooth. Another approach to improve collection efficiency is the use of a circular cone attachment that is placed between the bottom section of the cyclone and top section of the collection bottle (Takeda *et al*., 2011). This attachment can prevent resuspension of particles from the collection bottle because it is possible to decrease the air velocity in the collection bottle and to reduce the re-entrainment of particles from the collection bottle.

There are many previous studies regarding the effects of sole use of above mentioned two methods, reducing the surface roughness of inner wall of the cyclone and of using a circular cone attachment. However, the effect of combined use of these two methods have not been investigated. In this study, we examined the effectivity of the individual and combined effects of reducing the surface roughness of inner wall of the cyclone and of using a circular cone attachment in improving the collection efficiency of aerosol particles using a cyclone.

2. MATERIALS AND METHODS

2.1 Changing the Surface Roughness of the Inner Wall of the Cyclone

The HVS3 cyclone (CS3 Inc., USA) has been reported to have a 50% cutoff diameter of 0.1-0.2 μm at a flow rate of 1,100 L/min (Okuda *et al*., 2015; Rule *et al*., 2010). The surface roughness (average roughness, *R*a; JIS B0601, 2013) of the inner wall of this cyclone was measured as 5.1 μm using a surface-measuring unit (Handysurf E-45A, Tokyo Seimitsu, Japan). We used this as the "original" cyclone in our study. Another cyclone, which we refer to as the smoothened inner wall (SIW) cyclone, had the same inner shape as the HVS3 cyclone and was constructed of aluminum; its inner wall was ground and polished to reduce the surface roughness to *R*a = 0.08 μm. Schematics and photographs of both cyclones are shown in Fig. 1.

2.2 Constructing the Circular Cone Attachment

The shape and size of the cyclones tested in this study was similar to the cyclone tested by Takeda *et al*. (2011), who optimized the vertical angle of several circular cone attachments ranging from 40° to 80° and found that a 70° angle resulted in highest separation efficiency. We followed this approach in designing the shape and size of the circular cone attachment, which was constructed of aluminum (diameter (φ) 36-mm for the conical bottom and 70° for the vertical angle). The attachment is placed between the bottom section of the cyclone and the top section of the collection bottle, and can be adjusted in height (Fig. 2). In the present study, the height at which the attachment was positioned (*h*) was defined as the distance between the bottom of the tested cyclone and the top of the attachment.

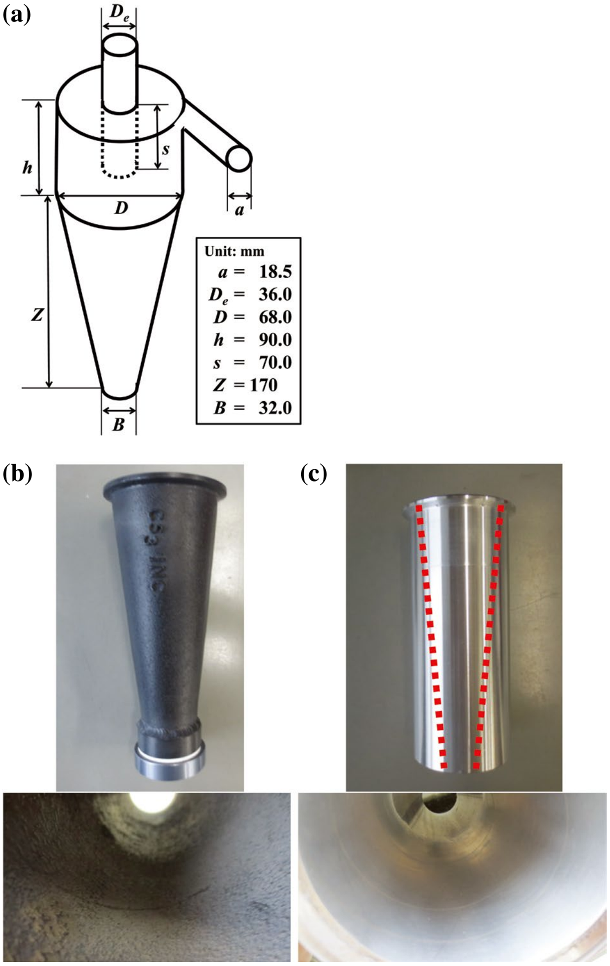

Fig. 1. Photographs of the cyclones used in this study. (a) Geometry of the cyclones, (b) The HVS3 cyclone and its interior, (c) the smoothened inner wall (SIW) cyclone and its interior.

2.3 Examining the Separation Characteristics of the Cyclones

Particle number concentration and size distribution at the inlet and outlet of (*i.e.* without and with) the cyclones were measured using a scanning mobility particle sizer (SMPS, Model 3910, TSI Inc., USA). An amber bottle (I-Chem 100 wide mouth amber glass jar, 250 mL, Thermo Fisher Scientific Inc., USA), which

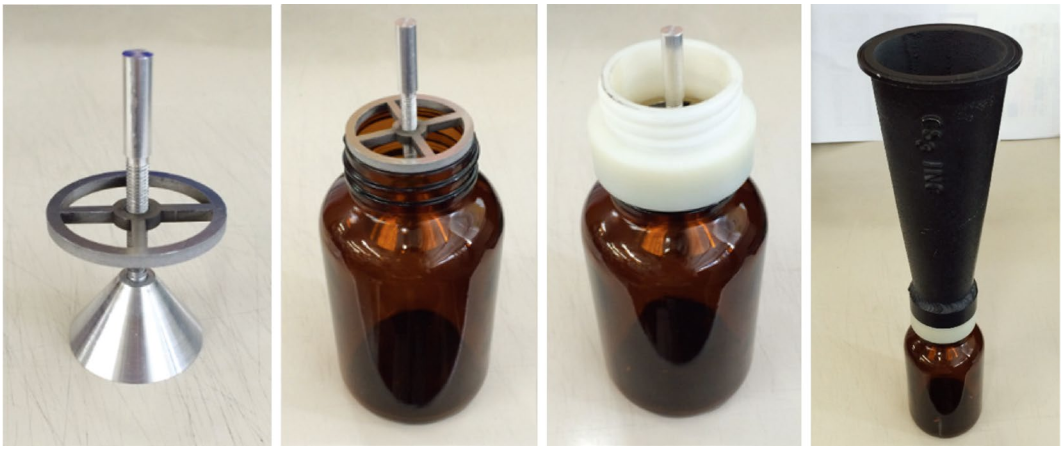

Fig. 2. Photographs of the circular cone attachment (diameter (φ) 36-mm for the conical bottom and 70° for the vertical angle) for the cyclone.

functioned as a particle collector, was connected to the cyclone. The air was pumped out using a blower (U2S-150, Showa Denki Co. Ltd., Japan). Air flow rate was controlled by an inverter (FRN2.2C1S-7J12, Fuji Electric Co. Ltd., Japan) and monitored using a mass flow meter (CMG400, Azbil Corp., Japan). The air flow rate was fixed to 1,100 L/min through the experiment because the HVS3 cyclone (original) has been reported to have a 50% cutoff diameter of 0.1-0.2 µm at that flow rate (Okuda *et al*., 2015; Rule *et al*., 2010). Pressure drop across the cyclone was measured using an electronic manometer (testo 506, testo AG, Germany). The experiment was carried out on the rooftop of a six-story building at Keio University, Yokohama, Japan. These experimental settings were the same as those used in a previous study (Okuda *et al*., 2015). We used sodium chloride particles for testing the separation characteristics of the cyclones. Specifically, NaCl particles were generated using a nebulizer and were then passed through a diffusion dryer that contained silica gel particles. The NaCl contained test air was mix with ambient air in order to achieve 1,100 L/min of the air flow rate. The particle concentrations in the range of 10-420 nm in the test air containing NaCl particles were at least two orders of magnitude higher than those in ambient air. Therefore, the particles in the ambient air would not affect the experimental result. The schematics of the experimental setup are shown in Fig. 3. Isokinetic probes were used in order to equalize the velocity of the air going into the analytical instrument to that goes toward the downstream. The split ratio (larger cross sectional area : smaller cross sectional area) of the first probe was 81 : 1, and that of the second probe was 18 : 1. The penetration of particles into the cyclones was calculated as the ratio of particle number concentration at the inlet to that at the outlet of the cyclones, expressed using equation (1):

$$Penetration_{cyclon}(d_p) = \frac{N_{outlet}(d_p)}{N_{inlet}(d_p)} \quad (1),$$

where d_p is the particle diameter, and N is the number concentration at each sampling point. N_{inlet} and N_{outlet} were measured by detaching/attaching the cyclones.

3. RESULTS AND DISCUSSION

3.1 Effect of Changing the Surface Roughness of the Inner Wall of the Cyclone

The penetration curves obtained in this study using the HVS3 cyclone (original, Ra = 5.1 µm) and the SIW cyclone (smoothened, Ra = 0.08 µm) are shown in Fig. 4. The penetration curve for the SIW cyclone is shifted toward a smaller particle diameter compared with that for the HVS3 cyclone, suggesting that the SIW cyclone would result in perform better in the collection of smaller particles. For example, the penetration of particles of 0.2 µm diameter was 70% for the HVS3 with 61% for the SIW cyclone, showing an approximate 10% improvement in the collection efficiency for the latter. We should note here that the 50% cutoff diameter of the original cyclone was 0.28 µm, and this was significantly larger than that reported by the previous studies (Okuda *et al*., 2015; Rule *et al*., 2010). Although we did not reach the concrete conclusion for this discrepancy, but possible explanations would be as follows. We used NaCl particles for the performance evaluation of the cyclone in this study whereas Okuda *et al*. (2014) used ambient aerosol particles. This may be

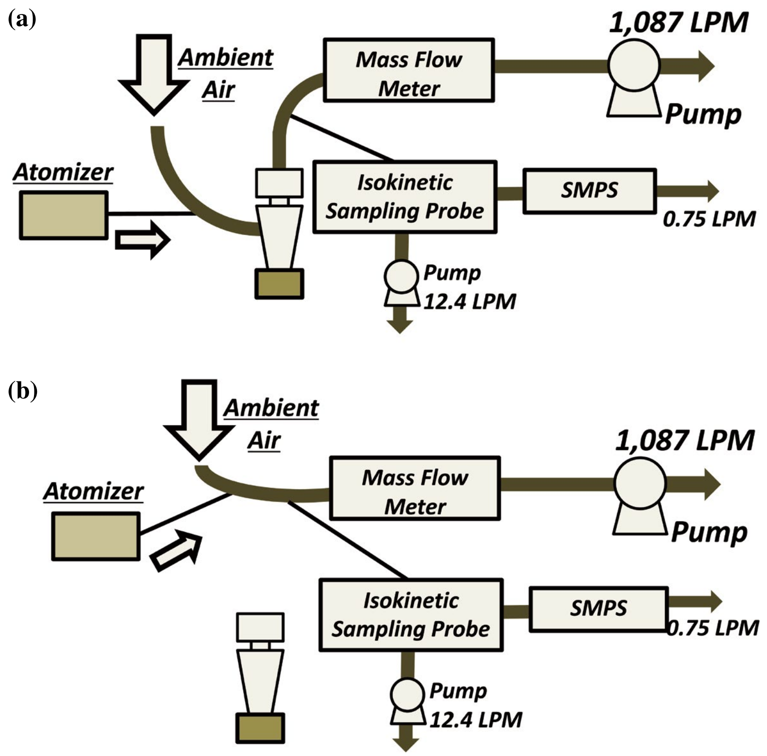

Fig. 3. Schematic diagrams of the experiments conducted to evaluate the particle penetration into the cyclones, (a) with the cyclone (as outlet), and (b) without the cyclone (as inlet).

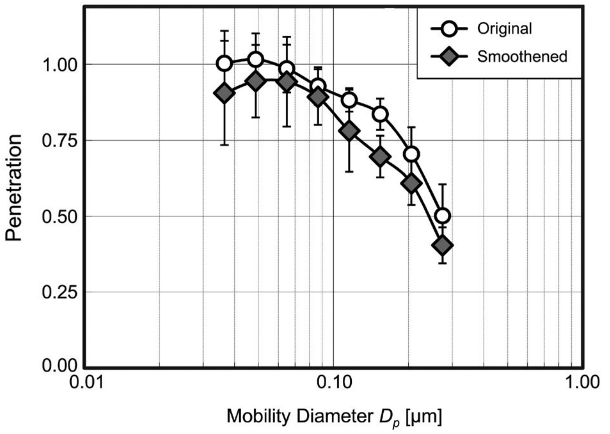

Fig. 4. Penetration curves for the HVS3 cyclone (original) and the SIW cyclone (smoothened) at a flowrate of 1,100 L/min.

the reason for the difference in the results of the performance evaluation. Another possibility is the effect of humidity, which may affect the particle size distribution; however, according to our experimental results no clear relationships was found between the separation performance and humidity. Changing the surface material of cyclone may affect the incoming aerosol particle collection due to the difference in electrostatic force (Okuda *et al.*, 2015; Gen *et al.*, 2014); however, this topic is out of the scope of this study. Rule *et al.* (2010), who did not use an SMPS for the performance evaluation of the cyclone, did not show the detailed penetration curves while we showed them in this paper, so that we could not do further discussion on this discrepancy.

We estimated the effect of the improved collection efficiency in combination with the reduction in surface roughness of the inner wall, and compared this to the experimental results. The friction coefficient λ can be predicted using the Reynolds number Re and relative roughness ε/d from the Moody chart, where ε is the mean profile height of the roughness of the pipe (average roughness Ra in this study) and d is the pipe diameter (Kaya *et al.*, 2011). The pressure drop ΔP is proportional to the friction coefficient and can be expressed using equation (2):

$$\Delta P = \lambda \frac{\rho L v^2}{2d} \quad (2),$$

where ρ is the density of the fluid, v is the average velocity, λ is the friction factor from the Moody chart,

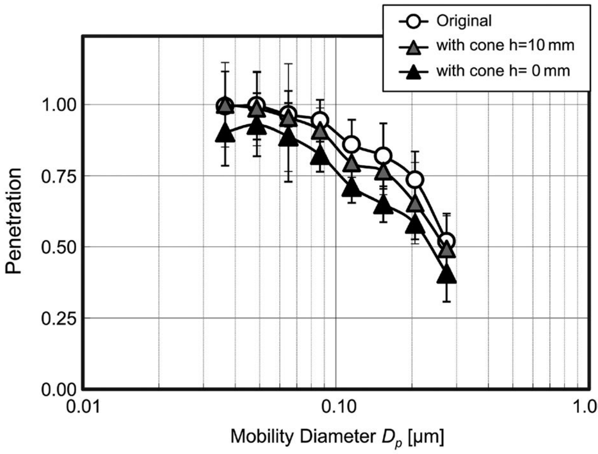

Fig. 5. Penetration curves for the HVS3 cyclone without (original) and with the circular cone attachment ($h = 0$ and 10 mm), at a flowrate of 1,100 L/min.

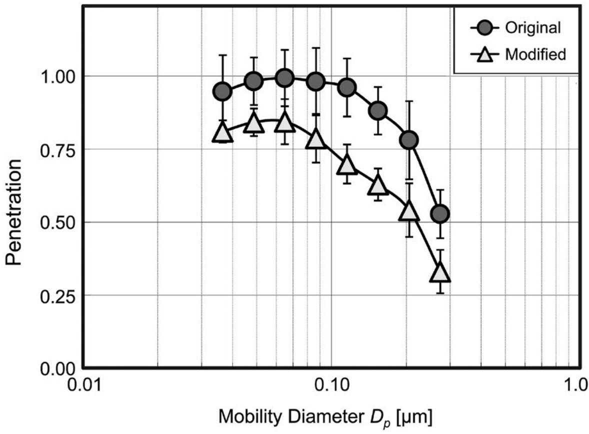

Fig. 6. Penetration curves for the HVS3 cyclone without the attachment (original) and for the SIW cyclone with the circular cone attachment (modified; $h = 0$) at a flowrate of 1,100 L/min.

and L is the length of the pipe (Kaya *et al.*, 2011; Karagoz and Avci, 2005). In this study, ρ, L and d were constant. According to the Moody chart, an inlet velocity $v = 70$ m/s, $Re = 8.5 \times 10^4$, and $\varepsilon/d = 2.8 \times 10^{-4}$ resulted in $\lambda_{\mathrm{HVS}} = 0.021$ for the HVS3 cyclone; the same inlet velocity and Re but $\varepsilon/d = 4.4 \times 10^{-6}$ resulted in $\lambda_{\mathrm{SIW}} = 0.018$ for the SIW cyclone. Therefore, the ratio $\lambda_{\mathrm{HVS}}/\lambda_{\mathrm{SIW}}$ was 1.167. In this study, the actual pressure drop ($\Delta P = 82$ hPa) was similar for both cyclones; therefore, the friction coefficient λ was inversely proportional to v^2. Since the centrifugal force of a particle in a cyclone is proportional to v^2, the collection efficiency of the SIW cyclone was hence superior to the HVS3 cyclone. According to Asbach *et al.* (2011), the 50% cutoff diameter of particles d_{p50} is proportional to $v^{-1/3}$, which means that the 16.7% difference in λ would resulted in an approximate 5% difference in d_{p50}. Consequently, the effect of reducing the surface roughness of the inner wall of cyclones is estimated as an approximate 5% improvement in terms of the 50% cutoff diameter which supports the experimental results obtained in this study.

3. 2 Effect of Using the Circular Cone Attachment

The penetration curves obtained in this study using the HVS3 cyclone without (original) and with the attachment ($h = 0$ mm, or 10 mm) are shown in Fig. 5. The penetration curve for the cyclone with the attachment ($h = 0$ mm) was shifted toward a smaller particle diameter compared with the cyclone without the attachment, whereas the difference in the penetration curve for the $h = 10$ mm attachment and that without the attachment was unclear. The cyclone with $h = 10$ mm attachment may still allow the particle resuspension from the collection bottle. Consequently, the cyclone with the higher installed position of the attachment resulted in superior collection efficiency of aerosol particles compared with that without the attachment.

3. 3 Combined Effect of Smoothened Inner Wall and Using Circular Cone Attachment

The penetration curves obtained in this study for the HVS3 cyclone without a circular cone attachment (original) and for the SIW cyclone with an attachment (modified; $h = 0$) are shown in Fig. 6. The penetration curve for the SIW cyclone was shifted toward a smaller particle diameter. The 50% cutoff diameter of the modified cyclone was 0.23 μm, whereas that of the original cyclone was 0.28 μm. The combined use of the smoothened inner wall and the circular cone attachment thus resulted in improved collection efficiency of aerosol particles.

The techniques presented in this study can be used to improve the aerosol particle collection efficiency of cyclones without the use of a filter. This may be useful for future studies, e.g., exposure experiments using aerosol particles for toxicity evaluation, and the determination of physical and chemical characteristics of aerosol particles related to human health (Ogino *et al.*, 2017; Hatoya *et al.*, 2016; Okuda *et al.*, 2015; Okuda, 2013).

4. CONCLUSION

To improve the collection efficiency of the HVS3 cyclone (Okuda *et al.*, 2015; Rule *et al.*, 2010), the individual and combined effects of reducing the surface roughness of the inner wall of the cyclone and of using a circular cone attachment were tested. Individually, each of these techniques improved the collection efficiency of the cyclone, and their combined use resulted in an even more improvement.

ACKNOWLEDGEMENT

This study was supported partly by the Environment Research and Technology Development Fund (5-1651) of the Ministry of the Environment, Japan, the Matching Planner Program from Japan Science and Technology Agency, JST (MP28116789653), JKA foundation (27-127), Steel Foundation for Environmental Protection Technology, Grant for Environmental Research Projects from The Sumitomo Foundation, “Super Egg Program” System for the Development of Future Scientific Technologies of Keio University, the Keio Leading-edge Laboratory of Science and Technology (KLL) Specified Research Projects, and Keio Gijuku Academic Development Funds.

REFERENCES

Asbach, C., Fissan, H., Kaminski, H., Kuhlbusch, T.A.J., Pui, D.Y.H., Shin, H., Horn, H.G., Hase, T. (2011) A low pressure drop preseparator for elimination of particles larger than 450 nm. Aerosol and Air Quality Research 11, 487-496.

Dockery, D.W., Pope III, C.A., Xu, X., Spengler, J.D., Ware, J.H., Fay, M.E., Ferris Jr., B.G., Speizer, F.E. (1993) An association between air pollution and mortality in six U.S. cities. New England Journal of Medicine 329, 1753-1759.

European Parliament and of the Council (2008) Ambient air quality and cleaner air for Europe. Directive 2008/50/EC, May 21.

Gen, M., Ikawa, S., Sagawa, S., Lenggoro, I.W. (2014) Simultaneous deposition of submicron aerosols onto both surfaces of a plate substrate by electrostatic forces. e-Journal of Surface Science and Nanotechnology 12, 238-241.

Hatoya, K., Okuda, T., Funato, K., Inoue, K. (2016) Online measurement of the surface area concentration of aerosols in Yokohama, Japan, using the diffusion charging method. Asian Journal of Atmospheric Environment 10, 1-12.

International Agency for Research on Cancer (2013) Air Pollution and Cancer. IARC Scientific Publication No. 161, Lyon, France.

Japan Industry Standards Committee (2013) Geometrical Product Specifications (GPS)-Surface texture: Profile method-Terms, definitions and surface texture parameters. JIS B 0601.

Karagoz, I., Avci, A. (2005) Modelling of the pressure drop in tangential inlet cyclone separators. Aerosol Science and Technology 39, 857-865.

Kaya, F., Karagoz, I., Avci, A. (2011) Effects of surface roughness on the performance of tangential inlet cyclone separators. Aerosol Science and Technology 45, 988-995.

Lelieveld, J., Evans, J.S., Fnais, M., Giannadaki, D., Pozzer, A. (2015) The contribution of outdoor air pollution sources to premature mortality on a global scale. Nature 525, 367-381.

Lichtveld, K.M., Ebersviller, S.M., Sexton, K.G., Vizuete, W., Jaspers, I., Jeffries, H.E. (2012) In vitro exposures in diesel exhaust atmospheres: resuspension of PM from filters versus direct deposition of PM from air. Environmental Science and Technology 46, 9062-9070.

Ministry of Environment, Japan (2009) Environmental Quality Standards for the $PM_{2.5}$. Notification #33, September 9 (in Japanese).

OECD (2012) OECD Environmental Outlook to 2050: The Consequences of Inaction. OECD Publishing, Paris. http://dx.doi.org/10.1787/9789264122246-en.

Ogino, K., Nagaoka, K., Okuda, T., Oka, A., Kubo, M., Eguchi, E., Fujikura, Y. (2017) $PM_{2.5}$ induced airway inflammation and hyperresponsiveness in NC/Nga mice. Environmental Toxicology 32, 1047-1054.

Ogino, K., Takahashi, N., Kubo, M., Takeuchi, A., Nakagiri, M., Fujikura, Y. (2014) Inflammatory airway responses by nasal inoculation of suspended particulate matter in NC/Nga mice. Environmental Toxicology 29, 642-654.

Okuda, T. (2013) Measurement of the specific surface area and particle size distribution of atmospheric aerosol reference materials. Atmospheric Environment 75, 1-5.

Okuda, T., Isobe, R., Nagai, Y., Okahisa, S., Funato, K., Inoue, K. (2015) Development of a high-volume $PM_{2.5}$ particle sampler using impactor and cyclone techniques. Aerosol and Air Quality Research 15, 759-767.

Okuda, T., Yoshida, T., Gunji, Y., Okahisa, S., Kusdianto, K., Gen, M., Sato, S., Lenggoro, I.W. (2015) Preliminary study on the measurement of the electrostatic charging state of $PM_{2.5}$ collected on filter media. Asian Journal of Atmospheric Environment 9, 137-145.

Pope III, C.A., Thun, M.J., Namboodiri, M.M., Dockery, D.W., Evans, J.S., Speizer, F.E., Heath Jr., C.W. (1995) Particulate air pollution as a predictor of mortality in a prospective study of U.S. adults. American Journal of Respiratory and Critical Care Medicine 151, 669-674.

Rule, A.M., Geyh, A.S., Ramos-Bonilla, J.P., Mihalic, J.N., Margulies, J.D., Polyak, L.M., Kesavan, J., Breysse, P.N. (2010) Design and characterization of a sequential cyclone system for the collection of bulk particulate matter. Journal of Environmental Monitoring 12, 1807-1814.

Takeda, N., Nishimura, Y., Ozawa, K., Yamamoto, T., Fukui, K., Yoshida, H. (2011) Improvement of particle separation performance by modified dry-cyclone. Journal of the Society of Powder Technology, Japan 48, 840-846 (in Japanese).

USEPA (2013) National Ambient Air Quality Standards for Particulate Matter; Final Rule, Federal Register 78, January 15.

Van Winkle, L.S., Bein, K., Anderson, D., Pinkerton, K.E., Tablin, F., Wilson, D., Wexler, A.S. (2015) Biological dose response to $PM_{2.5}$: Effect of particle extraction method on platelet and lung responses. Toxicological Sciences 143, 349-359.

Yoshida, H., Saeki, T., Hashimoto, K., Fujioka, T. (1991) Size classification of submicron powder by air cyclone and three-dimensional analysis. Journal of Chemical Engineering of Japan 24, 640-647.

Zhou, L.X., Soo, S.L. (1990) Gas-solid flow and collection of solids in a cyclone separator. Powder Technology 63, 45-53.

(Received 16 January 2017, revised 31 March 2017, accepted 31 March 2017)