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Inertial Classification of Nanoparticles with Fibrous Filters

Yoshio Otani[1*], Kazunobu Eryu[1], Masami Furuuchi[1], Naoko Tajima[2], Perapong Tekasakul[3]

[1] *Graduate School of Natural Science and Technology, Kanazawa University, Kakuma, Kanazawa 920-1192, Japan.*
[2] *Kanomax Japan Inc., 2-1 Shimizu, Suita, Osaka 565-0805, Japan*
[3] *Department of Mechanical Engineering, Faculty of Engineering Prince of Songkla University, Hat Yai, Songkhla 90112, Thailand*

Abstract

This paper proposes a new concept for the utilization of fibrous filters for the classification of nanoparticles. The present work confirmed that the filter employed in the present work can separate particles smaller than 100 nm. The main conclusions obtained in the present work are as follows: (1) Inertial filter utilizes inertial impaction of particles and the classification performance can be predicted by the log penetration law and the single fiber collection efficiency, (2) 50% cutoff size is reduced by increasing the filtration velocity and is predicted by $Stk_{50} = 1$, (3) Inertial filter developed in the present work has a low pressure drop compared to a low pressure impactor and therefore the volatilization of volatile organic compounds is suppressed during the atmospheric aerosol sampling.

Keywords: Nanoparticles; Fibrous filters; Inertial filtration; High filtration velocity; Brownian diffusion.

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[*] Corresponding author. Tel: 81-76-234-4813; Fax: 81-76-264-6239
E-*mail address*: otani@t.kanazawa-u.ac.jp

INTRODUCTION

Since the six cities study (Dockery *et al*., 1993) revealed that mortality is related to $PM_{2.5}$ annual concentration more closely than that of PM_{10}, there is an increasing interest on the adverse health effect of finer and finer particles. In order to assess the health effect of these particles, the primary work is to determine the chemical compositions of particles with respect to particle size because inhaled particles are deposited in different regions of the lung depending on the particle size. However, in order to conduct various chemical analyses for atmospheric fine particles, we must collect a fairly large amount of particles by filtering atmospheric air with filters, say in the order of mg for obtaining sufficient quantitative accuracies. Although particles smaller than 0.1 μm account for a large portion in number, it is very small in mass. Therefore, the collection of a sufficient mass of atmospheric nanoparticles requires a long sampling time. Besides the assessment of health effects of nanoparticles, the classification of nanoparticles is becoming more important in the manufacturing of various semiconductor devices from nanoparticles through CVD processes because the inclusion of large particles in deposited film may deteriorate the performance (Kruis *et al*., 1998).

Differential mobility analyzers, DMA (Knutson and Whitby, 1975) and low pressure impactors, LPI (Hering *et al*., 1978, 1979, Kauppinen and Hillamo *et al*., 1989) are the main classifiers for nanoparticles available at present. DMA can classify particles with the size range between around 1 nm and 1 μm, but the sampling flow rate is relatively small and the faction of classified nanoparticles is small because of the low charging efficiency for finer particles, resulting in long time to collect atmospheric nanoparticles the mass of which is sufficient for the various chemical analyses. Furthermore, one may suspect the size change and the composition change due to the volatilization and decomposition of unstable chemical species when the particles pass through the charger and the classification region. LPI can also classify nanoparticles at a fairly high airflow rate, but the evaporation of unstable chemical species is inevitable because LPI is operated at low pressures. Through both industrial and health-effect matters on nanoparticles, the classification of nanoparticles is very important and the methods for the classification should be well established.

Air filters are commonly used to remove airborne particles in order to obtain clear air. Since air filters utilizes various collection mechanisms, they have the most penetrating particle sizes (MPPS), depending on the filtration conditions and the filter structures. However, by utilizing MPPS, i.e., by properly selecting the filter structures and the filtration conditions, we may classify particles with filters. The objective of the present work is to assess the possibility of air filter for classifying particles especially nanoparticles.

PRINCIPLE OF INERTIAL FILTER

Large particles are collected in a conventional filter by inertial impaction at a high filtration velocity while small particles are removed from air by Brownian diffusion as shown in Fig.1. The measures for inertial impaction and Brownian diffusion are Stokes number and Peclet number; where C_c is the Cunningham slip correction factor, ρ_p the particle density, d_p the particle diameter, u the filtration velocity, μ the viscosity, d_f the fiber diameter, and D the Brownian diffusivity of particles.

$$Stk = \frac{C_C \rho_p d_p^2 u}{9\mu\ d_f} \tag{1}$$

$$Pe = \frac{u\ d_f}{D} \tag{2}$$

The collection efficiency of a filter increases with increasing Stk and decreasing Pe. Therefore, by using an extremely high filtration velocity we may achieve high collection efficiency for larger particles and low collection efficiency for smaller particles, i.e., classification of particles.

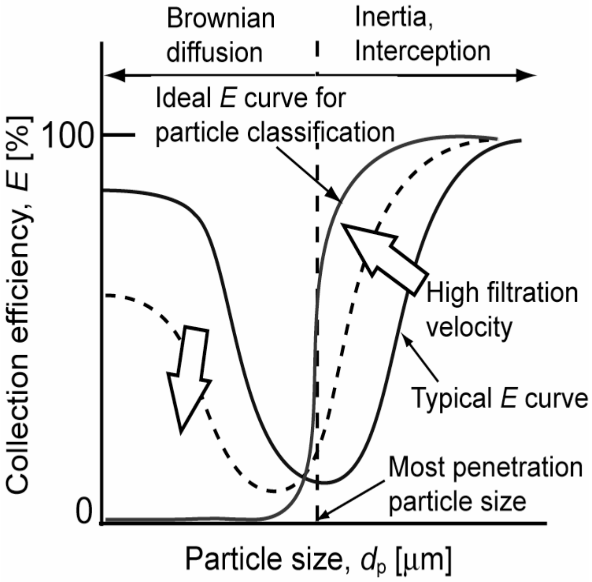

Fig. 1. Principle of inertial filtration.

EXPERIMENTS

The inertial filter is shown in Fig. 2. An 8-mm thick stainless steel fiber mat with fiber diameter of 8 μm and packing density of 0.0065 was used as a filter material. Since it has a high mechanical strength against the compression, it can maintain the filter structure at high filtration velocities and allows high filtration velocity through the filter at a given pressure drop through the filter.

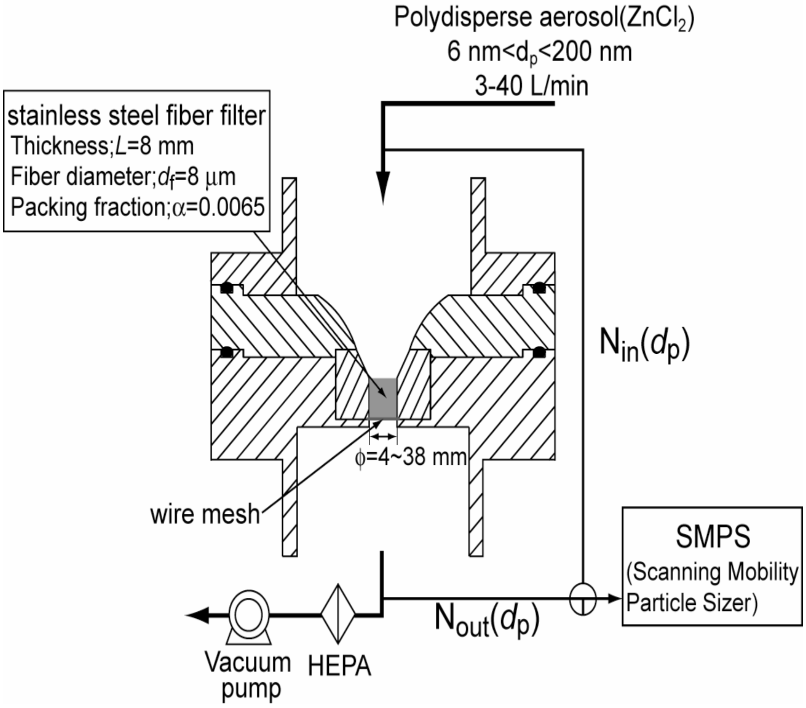

Fig. 2. Experimental setup.

Table 1. Experimental conditions.

Test filter	Unwoven stainless steal fiber filter Fiber diameter: 8 μm Thickness: 8 mm Packing density: 0.0065 Filtration area: ϕ 4 mm
Test aerosol	Polydisperse ZnO_2 particles
Filtration velocity	0.05–50 m/s (Volumetric flow rate: 3-40 L/min)

The fiber mat was packed in the throat of nozzle to achieve a high filtration velocity. Polydisperse zinc chloride particles with particle size range between 6 nm and 300 nm were generated with an evaporation-condensation type aerosol generator by changing the furnace temperature and passed though the filter. The inlet and outlet concentrations were measured by using a scanning mobility particle sizer (SMPS, TSI Inc., Model 3936N75) for the determination of classification performance of filters. The experimental conditions are shown in Table 1.

RESULTS AND DISCUSSION

Fig. 3 shows the changes in fractional collection efficiency with the filtration velocity. At a low filtration velocity of 0.05 m/s, the collection efficiency monotonically decreases with particle size. By increasing the filtration velocity to 5 m/s, the collection efficiency of particles smaller than 100 nm decreases because of less Brownian diffusion collection but that of particles larger than 100 nm remains rather small. At the filtration velocity of 20 m/s, the 50% cutoff diameter is about 100 nm but the collection efficiency of particles smaller than 100 nm remains at about 20%. However, with a further increase in filtration velocity, the collection efficiency of particles smaller than 100 nm keeps decreasing and that of particles larger than 100 nm starts to increase and, at the filtration velocity of 50 m/s, the collection efficiency curve becomes an ideal separation curve as shown in Fig. 1, where the collection efficiency of particles smaller than 20 nm is zero while that of those larger than 300 nm is equal to unity. By using the stainless steel fiber mat, it is possible to achieve 50% cutoff diameter of particles as small as 50 nm at the filtration velocity of 50 m/s.

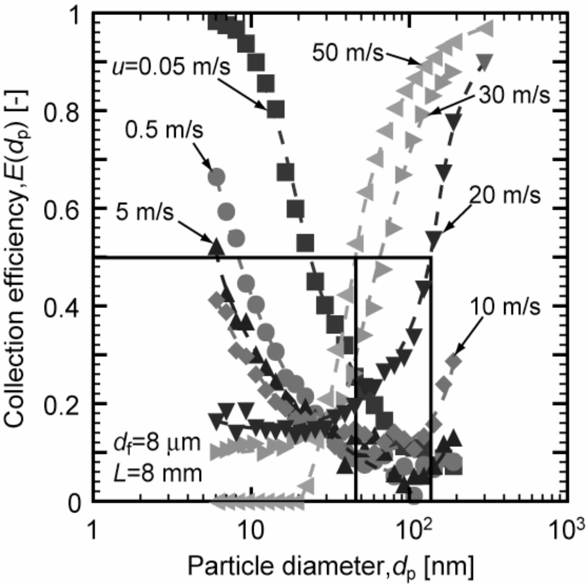

Fig. 3. Fractional collection efficiency of inertial filter at various filtration velocities.

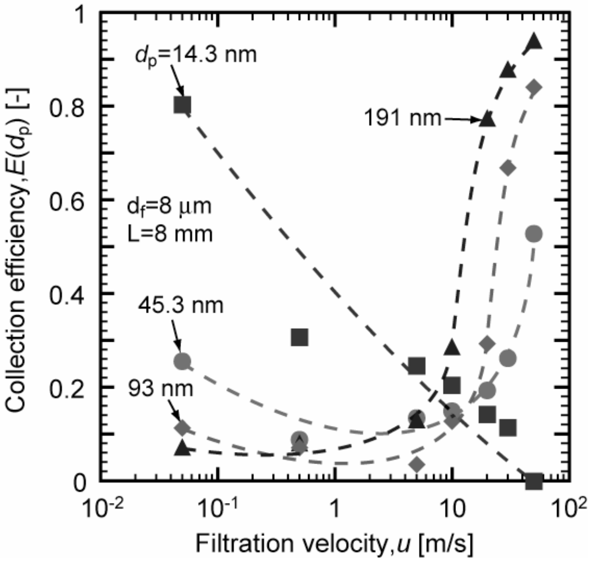

Fig. 4. Fractional collection efficiencies of inertial filter as a function of filtration velocity.

Fig. 4 shows the fractional collection efficiencies as a function of filtration velocity. The collection efficiency of 14.3-nm particles monotonically decreases with the filtration velocity because the collection is completely governed by Brownian diffusion. For particles with diameters of 45.3–191 nm at a filtration velocity lower than 10 m/s, the collection efficiencies are low because none of the collection mechanisms exert effectively. However, at a filtration velocity higher than 10 m/s, the fractional collection efficiency sharply rises because inertial collection becomes effective.

The fractional collection efficiencies are converted to single fiber collection efficiencies with the log-penetration equation of Eq. (3) and they are plotted against Peclet number and Stokes number, respectively in Figs. 5 and 6.

$$\ln\frac{C_{out}}{C_{in}} = \ln(1-E) = -\frac{4\alpha L}{\pi d_f(1-\alpha)}\eta \tag{3}$$

where C_{out} and C_{in} are the particles concentrations at filter inlet and outlet, E the filter collection efficiency, α the packing density, L the filter thickness and η the single fiber collection efficiency. As seen in Fig. 5, the single fiber collection efficiencies of smaller particles at the filtration velocities of 0.05 and 0.5 m/s collapse onto a single straight line with the slope equal to -2/3 (Kirsch and Stechkina, 1968) while those at higher velocities fall on a single curve with the slope of -1/2 (Natanson, 1957). The collapse of single fiber collection efficiencies onto single curves when plotted against Pe confirms that small particles are captured solely by Brownian diffusion. On the other hand, as shown in Fig. 6, the single fiber collection efficiencies of larger particles at a high filtration velocity fall onto a single curve against *Stk*, indicating that larger particles are collected only by inertia at a high filtration velocity.

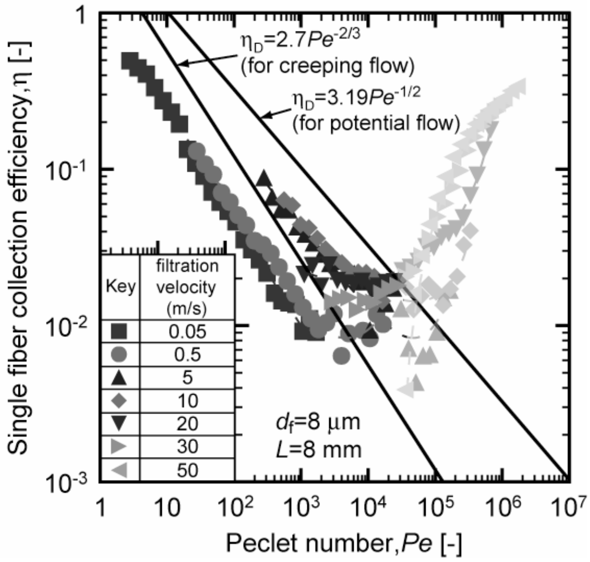

Fig. 5. Single fiber collection efficiencies of inertial filter as a function of Peclet number.

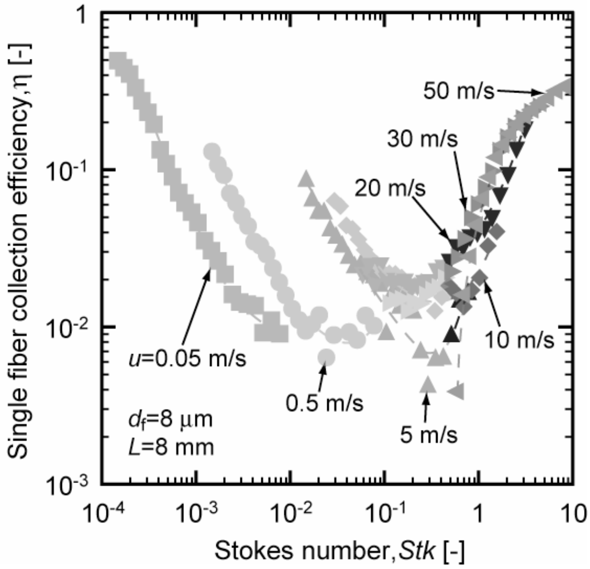

Fig. 6. Single fiber collection efficiencies of inertial filter as a function of Stokes number.

Fig. 7 compares the classification performance of inertial filter at the filtration velocity of 50 m/s with that of an impactor which has a solid impaction plate (Ranz and Wong, 1952). As seen from the figure, the slopes of the two curves are almost the same when the collection efficiency is smaller than 0.8, suggesting that the inertial filter has almost the same classification performance as the solid plate impactor. From Fig. 7, the inertial filter can be designed according to the following simple law:

$$Stk_{50} = 1 \tag{4}$$

Incidentally, the tailing at a high collection efficiency of inertial filter may be attributed to the particle bounce-off on fibers upon impaction or the change in filter structure due to the filter compression with air at high filtration velocities.

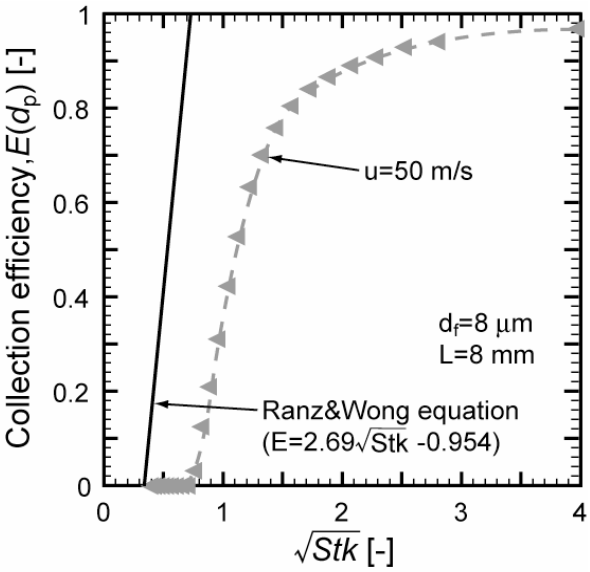

Fig.7. Comparison of classification performance of inertial filter with that of solid plate impactor.

The pressure drop of inertial filter is shown in Fig. 8. The pressure drop increases with the filtration velocity and it is 28 kPa at the filtration velocity of 50 m/s. The pressure drop is relatively small compared to a low pressure impactor (90 kPa). The low pressure drop of inertial filter is advantageous when sampling atmospheric aerosols, i.e., HEPA filters placed downstream of the inertial filters can collect particles smaller than 100 nm without any significant changes in particle composition due to the evaporation of volatile species under the reduced pressures. Furthermore, by increasing the filtration area of inertial filter, we can achieve high sampling flow rate to collect particle masses sufficient to the chemical analysis, which in turn makes it possible to measure the composition changes in particles with a high time resolution.

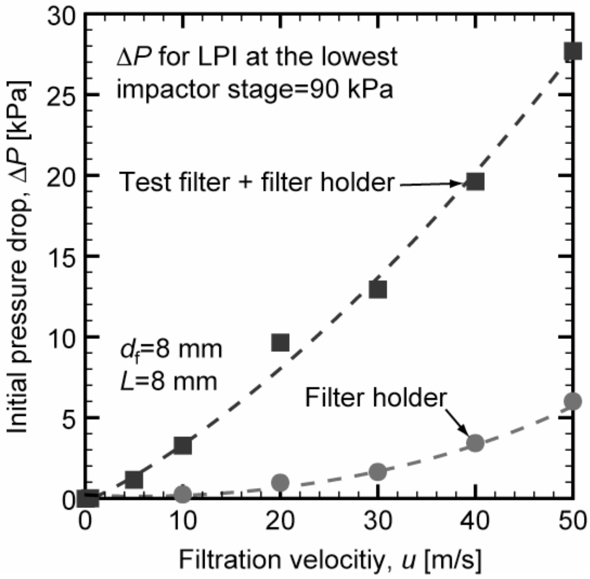

Fig. 8. Pressure drop of inertial filter as a function of filtration velocity.

Changing the cutsize with the inertial filter is not as easy as an impactor. If we want to lower the cutsize, we have to enhance inertial collection of larger particles and, at the same time, lower the diffusion collection of smaller particles. At the constant filtration velocity, the decrease in fiber size brings an increase in both inertial and diffusion effects, making the penetration curve concave against the particle diameter. In this case, we have to further raise the filtration velocity, but the increase in filtration velocity also leads to the filter compression by the airflow. Consequently, changing the cutsize is to find an compromise between a high filtration velocity and a finer fiber filters which withstands at the high filtration velocity.

CONCLUSIONS

The present work proposes a new concept for the utilization of fibrous filters for the classification of nanoparticles. The present work confirmed that the filter employed in the present work can separate particles smaller than 100 nm. By selecting an appropriate filter structure and fiber diameter, it is possible to develop a classifier for separating smaller particles. The main conclusions obtained in the present work are as follows:

(1) Inertial filter utilizes inertial impaction of particles and the classification performance can be predicted by the log penetration law and the single fiber collection efficiency.

(2) 50% cutoff size is reduced by increasing the filtration velocity and is predicted by $Stk_{50} = 1$.

(3) Inertial filter developed in the present work has a low pressure drop compared to a low pressure impactor and therefore the volatilization of volatile compounds is suppressed during the sampling.

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