



Influence of Filter Inhomogeneity on Air Filtration of Nanoparticles

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ABSTRACT

Thermal rebound of nanoparticles on the surface of fibers is of big concern in collecting nanoparticles. Another factor influencing the collection of nanoparticles is the inhomogeneity of fiber packing. The present work studied the influence of filter inhomogeneity on the collection efficiency of nanoparticles by using wire screens as uniform structure in comparison to real filters. As a result, the single fiber collection efficiencies of nanoparticles through wire screens are in good agreement with those predicted by Kirsch and Fuchs ($\eta_D = 2.7Pe^{-2/3}$), but the dependence of real filters on Pe is somewhat smaller than $-2/3$ and in agreement with ($\eta_D = 0.84Pe^{-0.43}$, Wang *et al.*, 2007). The dependence of single fiber collection efficiency on Pe for the real filters is well explained by considering non-uniformly packed filter consisting of two regions of densely packed and loosely packed fibers.

Keywords: Collection efficiency; Diffusional regime; Fiber packing inhomogeneity; Pressure drop.

INTRODUCTION

Nanoparticles are of great interest as a new functional material but at the same time the adverse health effect is also of great concern because of their high reactivity and large surface area. As far as the collection of airborne nanoparticles with fibrous air filters concerns, it seems that air filters are very effective since the motion of nanoparticles are governed by Brownian diffusion and the diffusivity is almost the same as gas molecules. Therefore, the collection efficiency seems to be readily predicted by the conventional diffusion collection theory (Kirsch and Fuchs, 1968). However, Wang and Kasper (1991) pointed out that as the size of particle decreases, thermal rebound may reduce the collection efficiency. Since the publication of this paper, many researches tried to measure the reduction in collection efficiency by thermal rebound on fiber surfaces (Otani *et al.*, 1995; Ichitsubo *et al.*, 1996; Alonso *et al.*, 1997; Heim *et al.*, 2005; Kim *et al.*, 2007) However, because of difficulty in generating monodisperse single-digit nanoparticles and their detection, we do not have rigid reliable data for the reduction in collection efficiency. Judging from the data reported so far, it is said that the thermal rebound does not occur or does not play any significant role for the collection of particles as small as 2 nm. Other than the thermal rebound, Wang *et al.* (2007) claimed that the exponent of

Peclet number, Pe , in single fiber collection efficiency is not $-2/3$ but somewhat smaller than $-2/3$. Podgorski (2009) and Guillaume *et al.* (2009) also observed smaller dependence on Pe , and claimed that the fiber size distribution and pinholes are the cause of smaller dependence on Pe .

In the present paper, we hypothesized that the inhomogeneity in fiber packing would be the cause of smaller dependence on Pe and constructed a model to predict the collection efficiency based on the hypothesis and prove the hypothesis by comparing the model-based predictions with the experimental data.

EXPERIMENTAL

Experimental Apparatus

Fig. 1 shows the experimental setup for measuring the particle penetration. The test particles are NaCl particles, which are generated by evaporation/condensation type aerosol generator. The test particles are charged in charge equilibrium state as they pass through an ^{241}Am bipolar charger and classified into 10 nm to 50 nm by nano-DMA (Laboratory made). The DMA-classified particles are again passed through an ^{241}Am neutralizer and then charged particles are removed with a parallel-plate condenser to obtain neutral monodisperse nanoparticles.

The filtration velocities are varied from 0.03 to 0.5 m/s by diluting the aerosol with dry clean air upstream of the filter. When the flow is switched from the blank filter holder to the test filter holder, the flow rate is decreased because of the resistance of mounted filter. However, mass flow controller (MFC) connected downstream of the

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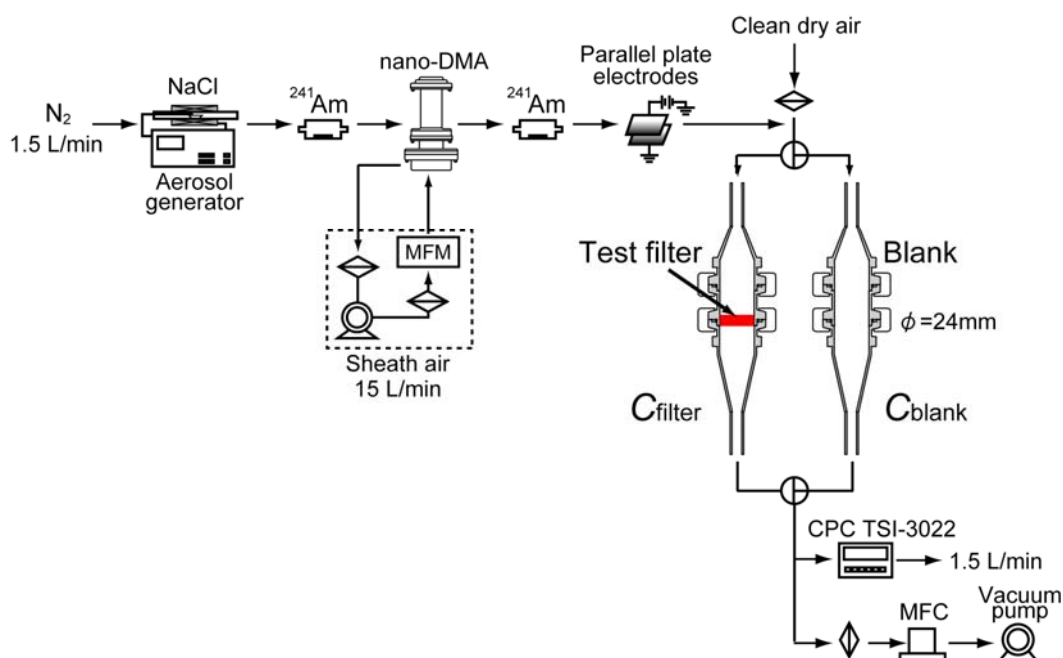


Fig. 1. Experimental apparatus.

holders automatically adjusts the flow rate to the prescribed flow rate. In the measurement of collection efficiency of nanoparticles, the particle loss due to diffusional deposition in conduits is of big concern. In the present work, two identical filter holders are used and they are connected in parallel so as to give the same particles loss in the conduits. Letting the outlet concentration of filter holder without a filter C_{blank} and that with a filter C_{filter} , the penetration is given by Eq. (1).

$$P = \frac{C_{\text{filter}}}{C_{\text{blank}}} \quad (1)$$

Although the above equation cancels out the loss of particles in the conduits, the experimentally evaluated loss of 10-nm particles in the conduit is as large as 10%. Therefore, with the present experimental setup, the correction for particle deposition loss is as much as 10%.

Test Filters

Wire screens as a uniformly packed filter and medium performance glass fiber filter and PP filter as a real filter were used. The major properties of these test filters are given in Table 1.

RESULT AND DISCUSSION

Nanoparticle Penetrations thorough Test Filters

Fig. 3 shows the particle penetration through the wire screens (a) and the fibrous filters (b), at filtration velocity of 0.05 m/s. The solid lines are the theoretical penetrations predicted by Kirsch and Fuchs (1968). As shown in these figures, the penetration becomes smaller with decreasing the particle size, suggesting that the Brownian diffusion is the dominant collection mechanism. For PP filter with high particle penetration, the experimental penetrations are in good agreement with the predicted ones, except the data for $d_p = 10$ nm. For medium performance filter, the experimental penetration is higher than the theory for all particle sizes tested in the study. The particle penetration, P , is converted to the single fiber collection efficiency, η , by the following log-penetrating equation:

$$\eta = -\frac{\pi}{4} \frac{1-\alpha}{\alpha} \frac{d_f}{L} \ln P \quad (2)$$

where α is the packing density of filter, L is the filter thickness, d_f is the fiber diameter. The packing density of wire screen shown in Table 1 was determined from the

Table 1. Test filter properties.

Filter	Wire screen (72 mesh)	Wire screen (150 mesh)	Medium performance filter	PP filter
Fiber material	SUS	SUS	Glass	Polypropylene
Fiber density, (kg/m ³)	7980	7980	2400	910
Thickness, L (mm)	0.06	0.12	0.38	0.28
Fiber diameter, d_f (μm)	30	60	2.1	9.5
Packing density, α (-)	0.215	0.276	0.088	0.172

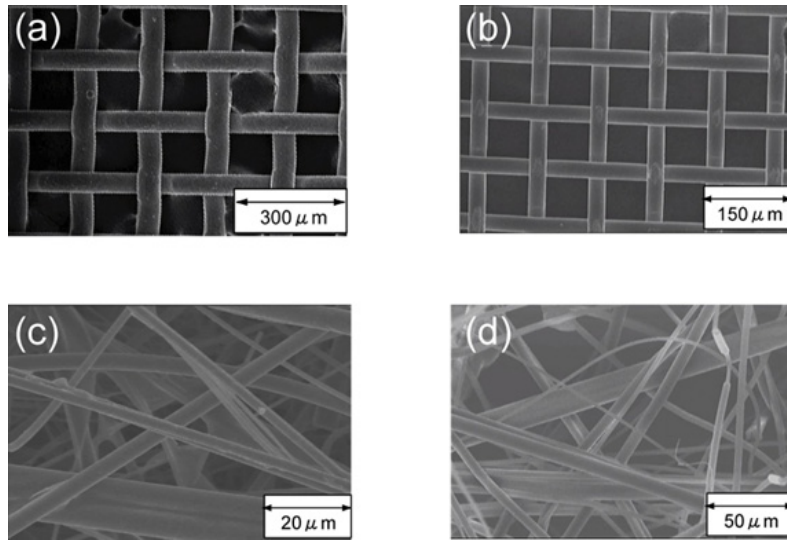


Fig. 2. SEM micrographs of test filters.

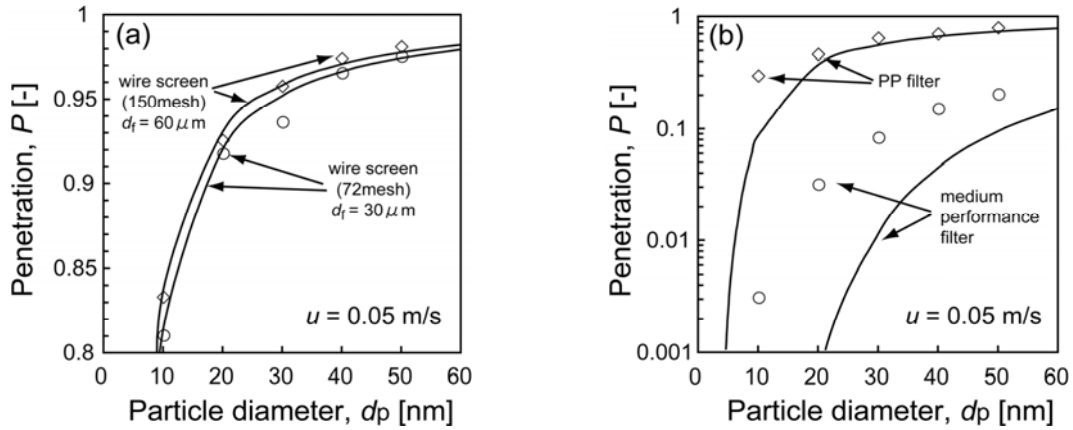


Fig. 3. Penetrations of NaCl particles through (a) wire screens and (b) fibrous filters.

geometry of wire screen because it has regular fiber arrangement. On the other hand, for fibrous filters, since they are very fluffy and difficult to measure the filter thickness, we employed the effective packing density, α' , which is determined from the pressure drop of filter by applying Davies equation. Davies equation is given by the following equation (Davies, 1952):

$$\Delta P = \frac{64\mu u L}{d_f^2} \alpha'^{1.5} (1 + 56\alpha'^3) \quad (3)$$

where μ is the air viscosity and u is the filtration velocity. Fig. 4 shows the single fiber collection efficiency for wire screens ((a) and (b)) and for fibrous filters ((c) and (d)). In these figures, dotted broken lines are predicted by the following equation (Kirsch and Fuchs, 1968):

$$\eta_D^{th} = 2.7Pe^{-2/3} \quad (4)$$

while broken lines are the empirical equation proposed by Wang *et al.* (2007):

$$\eta = 0.84Pe^{-0.43} \quad (5)$$

where Pe is the Peclet number defined by:

$$Pe = \frac{ud_f}{D} \quad (6)$$

where D is the diffusivity of particles. Figs. 4(a) and (b) for wire screens shows that the single fiber collection efficiency of wire screen is in good agreement with Eq. (4) over the whole range of Pe studied in the present work. On the other hand, in Figs. 4(c) and (d) for fibrous filters, the single fiber collection efficiency is in agreement with Eq. (5). Therefore, we may say that the deviation from Eq. (4) comes from non-uniformity in fiber packing because Eq. (4) gives good prediction for wire screen with regular fiber arrangement. Wang *et al.* (2007) also claimed that the deviation of experimental data from Eq. (4) comes from the inhomogeneity of fiber packing but they did not discuss this matter in detail. Therefore, our next effort is to construct a filter model which explains the deviation of

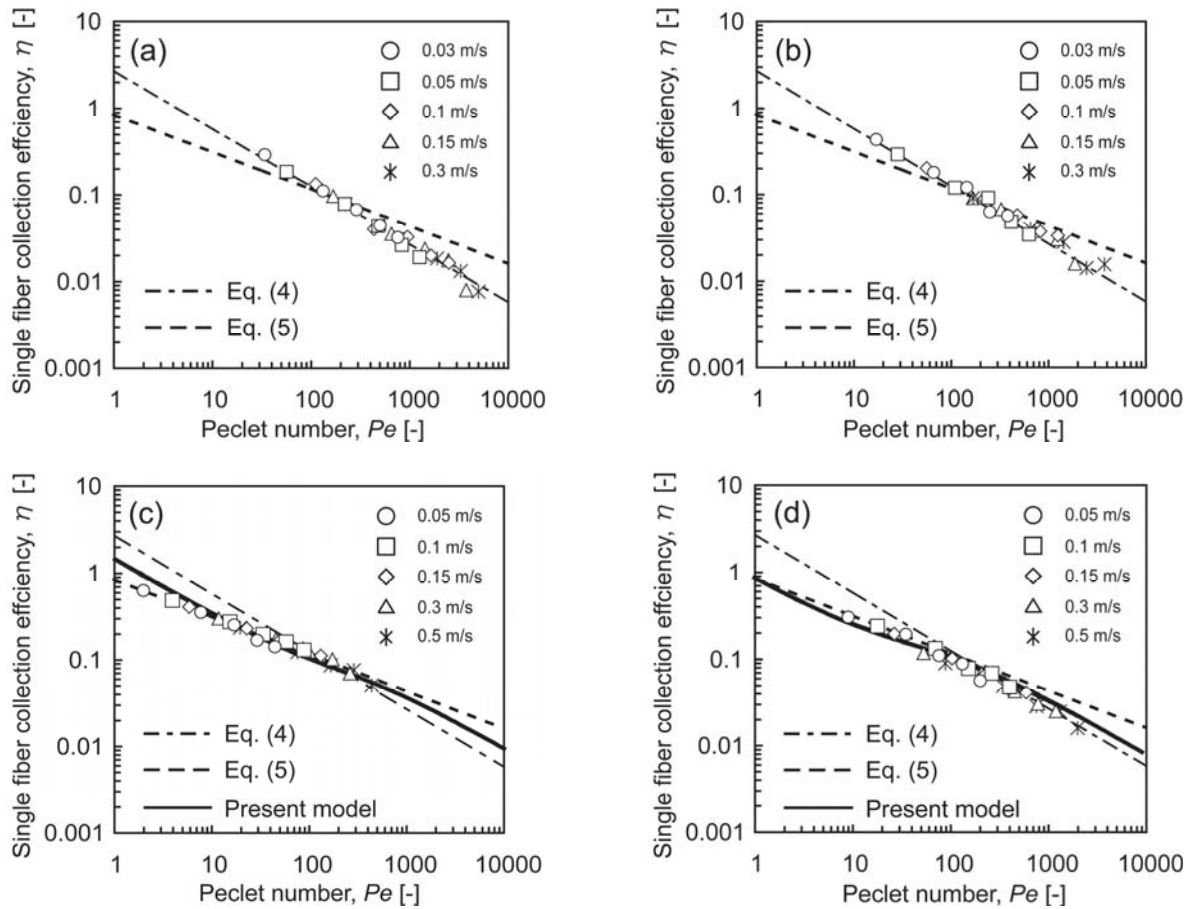


Fig. 4. Single fiber collection efficiency through wire screen of 72 mesh (a), wire screen of 150 mesh (b), medium performance filter (c) and PP filter (d).

experimental data from Eq. (4) by accounting for the inhomogeneity in fiber packing.

Model of Non-uniformly Packed Filter

Filter model proposed in the present work is illustrated in Fig. 5. In a real filter, densely and loosely packed fibers are distributed locally over the whole surface of filter but, here, for the sake of simplicity, we consider a filter, which consists of two parts, one of which is densely packed at the packing density of α_1 with the fraction of filter area of a and the other is loosely packed at α_2 with fractional area of $1 - a$, i.e., packing density-segregated filter. The average packing density of segregated filter, α_{model} , is given by:

$$\alpha_{\text{model}} = \alpha_1 a + \alpha_2 (1 - a) \quad (7)$$

The penetration of particles through the segregated filter model, P^{model} , is given by

$$P^{\text{model}} = \frac{C_{\text{in}} P_1 Q_1 + C_{\text{in}} P_2 Q_2}{C_{\text{in}} Q_0} = P_1 r + P_2 (1 - r) \quad (8)$$

where C_{in} is the inlet particle concentration, and Q is the volumetric flow rate. The subscripts 0, 1 and 2 denote, respectively, the total, the densely packed part and the

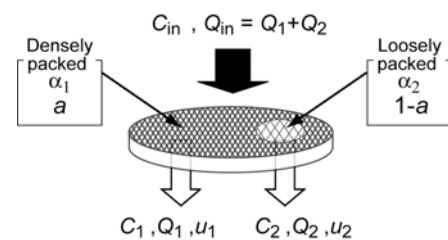


Fig. 5. Illustration of filter model.

loosely packed part of filter. r is the fraction of volumetric flow rate through densely packed filter over that total flow rate. By employing the superficial filtration velocity through filter, u , the fraction r is given by the following equation:

$$r = \frac{Q_1}{Q_0} = \frac{u_1 a A}{u_1 a A + u_2 (1 - a) A} = \frac{1}{1 + \frac{u_2 (1 - a)}{u_1 a}} \quad (9)$$

where A is the filter surface area. In order to calculate the penetration P^{model} , we must know P_1 , P_2 and r .

When an air flow is split into two flows and then the two flows merge, the volumetric flow rate is divided in such a way that the pressure drops of air flows after splitting are equal to each other:

$$\Delta P_1 = \Delta P_2 \quad (10)$$

where ΔP is the pressure drop. By introducing the drag coefficient of fiber to Eq. (10)

$$F_1 \mu u_1 l_1 = F_2 \mu u_2 l_2 \quad (11)$$

where F is the drag coefficient of fiber, and l is the total length of fiber per unit filter area.

We obtain the ratio of filtration velocities as

$$\frac{u_2}{u_1} = \frac{F(\alpha_1)l(\alpha_1)}{F(\alpha_2)l(\alpha_2)} \quad (12)$$

Substituting Eq. (12) into Eq. (9), we have

$$r = \frac{1}{1 + \frac{F(\alpha_1)l(\alpha_1)}{F(\alpha_2)l(\alpha_2)} \frac{1-a}{a}} \quad (13)$$

Consequently, if α_1 , α_2 and a are known, we can determine the fraction of volumetric flow rate through densely packed part.

Once α_1 , α_2 and a are known, we can also calculate the filtration velocities through the segregated filter by using Eq. (12) together with the continuity equation ($Q_0 = Q_1 + Q_2$). Then we may obtain P_1 and P_2 through Eq. (2) and Eq. (4), and the penetration of segregated filter by Eq. (8).

What follows from the above derivation is that we have to know three parameters, α_1 , α_2 and a in order to calculate the penetration of segregated filter. In determining these parameters, the objective function of Eq. (14), which is the square of difference between experimental penetration, P^{exp} , and the predicted one, P^{model} , is minimized

$$S = \sum_i (\ln P_i^{\text{exp}} - \ln P_i^{\text{model}})^2 \quad (14)$$

under the following constraints,

- (i) the pressure drop of segregated filter is equal to the experimental one,

- (ii) the average packing density given by Eq. (7) is equal to the measured packing density.

Fig. 6 compares the experimental penetrations with those predicted by the present model. The three parameters determined to fit the experimental data are given in Table 2. As seen in Fig. 6, one set of three parameters well describe the dependence of experimental penetrations on both particle diameter and filtration velocity for these filters. The single fiber collection efficiencies calculated by Eq. (2) from the predicted penetrations are plotted in Figs. 4(c) and (d) by solid lines. The solid lines are in good agreement with the experimental single fiber efficiency and the slope of single fiber collection efficiency against Pe is in agreement with that by Wang *et al.* Consequently, the present segregated filter model can explain the weaker dependence of single fiber efficiency on Pe .

In Table 2, we can see that the densely packed part occupies 69% of whole filter surface area for the medium performance filter, 76% for PP filter A and the packing density of densely packed part is about 3 times of loosely packed part, which is quite non-uniform. In order to improve the collection efficiency for nanoparticles, filters should be made with higher uniformity in fiber packing.

CONCLUSION

The single fiber collection efficiency through wire screens was in good agreement with the classical diffusion theory, but those of fibrous filters showed smaller dependence on Pe . This result confirms that the filter inhomogeneity leads to the smaller dependence on Peclet number. By constructing a segregated filter model which consists of densely and loosely packed parts of fibers, the dependence of single fiber collection efficiency on Pe was successfully explained.

Table 2. Parameters determined.

	α_1	α	a
medium performance filter	0.11	0.04	0.69
PP filter	0.21	0.06	0.76

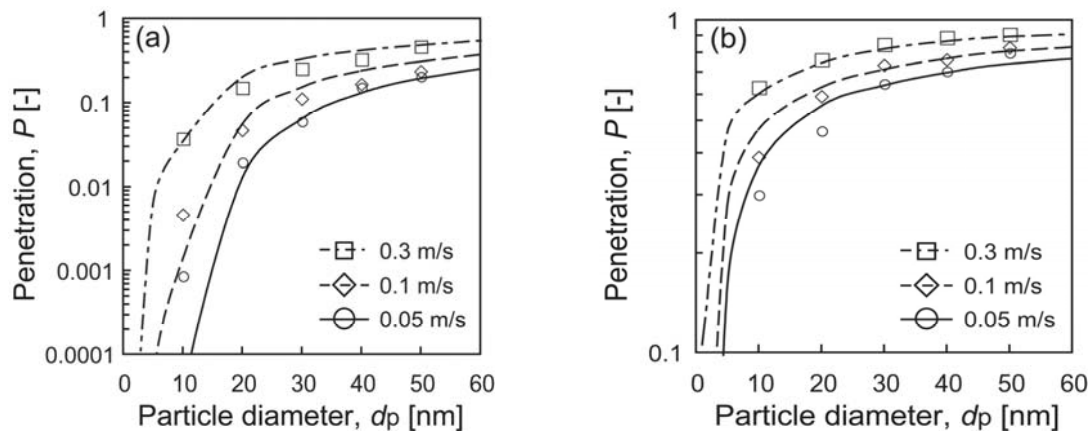


Fig. 6. Comparison of penetrations through medium performance filter (a) and PP filter (b) with those predicted by the present model.

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REFERENCES

- Alonso, M., Kousaka, Y., Hashimoto, T. and Hashimoto, N. (1997). Penetration of Nanometer-sized Aerosol Particles through Wire Screen and Laminar Flow Tube. *Aerosol Sci. Technol.* 27: 471–480.
- Davies, C.N. (1952). The Separation of Airborne Dust and Particle. *Proce. Inst. Mech. Eng.* 1B: 185–199.
- Guillaume, M., Dominique, T., Chazelet, S., Appert-Collin, J.C. and Bemer, D. (2009). Penetration of Nanoparticles through Fibrous Filters Perforated with Defined Pinholes. *J. Aerosol Sci.* 40: 762–775.
- Heim, M., Mullins, B.J., Wild, M., Meyer, J. and Kasper, G. (2005). Filtration Efficiency of Aerosol Particles below 20 Nanometers. *Aerosol Sci. Technol.* 39: 782–789.
- Ichitsubo, H., Hashimoto, T., Alonso, M. and Kousaka, Y. (1996). Penetration of Ultrafine Particles and Ion Clusters through Wire Screen. *Aerosol Sci. Technol.* 24: 119–127.
- Kim, C.S., Bao, L., Okuyama, K., Shimada, M. and Niinuma, H. (2007). Filtration Efficiency of a Fibrous Filter for Nanoparticles. *J. Nanopart. Res.* 8: 215–221.
- Kirsch, A.A. and Fuchs, N.A. (1968). Studies on Fibrous Aerosol Filters -III Diffusional Deposition of Aerosol in Fibrous Filter. *Ann. Occup. Hyg.* 11: 299–304.
- Otani, Y., Emi, H., Cho, S.J. and Namiki, N. (1995). Generation of Nanometer Size Particles and their Removal from Air. *Adv. Powder Technol.* 6: 272–281.
- Podgorski, A. (2009). Estimation of the Upper Limit of Aerosol Nanoparticles Penetration through Inhomogeneous Fibrous Filters. *J. Nanopart. Res.* 11: 197–207.
- Wang, H.C. and Kasper, G. (1991). Filtration Efficiency of Nanometer-size Aerosol Particles. *J. Aerosol Sci.* 22: 31–41.
- Wang, J., Chen, D.R. and Pui, D.Y.H. (2007). Modeling of Filtration Efficiency of Nanoparticles in Standard Filter Media. *J. Nanopart. Res.* 9: 109–115.

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