Present Status of Air Filters and Exploration of Their New Applications†

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Abstract

There is an increasing demand of air filters with a high collection performance, i.e., high collection efficiency and low pressure drop, for the application to indoor air cleaning. Air filters consisting of nanofibers have attracted great interests since they may have a low pressure drop because of slip flow effect and high collection efficiency due to enhanced interception effect. Although various nanofiber filters are available on the market, their collection performance is not as high as expected by the conventional filtration theory because non-uniform packing of fibers plays a significant role in the nanofiber filtration. In the present review, the present status of development of high performance air filters are reviewed. We may use air filters not only for the removal of particles but also for the classification of particles by selecting an appropriate filter by operating it under an optimized filtration condition for classification. Other topics introduced in the present review are the applications of filters and metal screen for aerosol classification and the use of centrifugal force for enhancing collection efficiency without increasing the pressure drop.

Keywords: air filtration, quality factor, nanofiber filter, aerosol classification, measurement

1. Introduction

Air filtration is the simplest and the most economical way of obtaining clean air. The first industrial application of air filter is dated back to AD 50 when woven cloths were used to filter breathing air in a mine. Air filtration theory for initial performance was established by Fuchs et al. and introduced in the treatise *Fundamentals of Aerosol Science* (Kirsch and Stechkina, 1978). Many problems were posed in this book but most of them still remain unresolved. Current research topics on air filtration may be summarized into the following three subjects:

1. Development of high performance air filters—high collection efficiency and low pressure drop
2. Change in collection performance with dust load—prediction of filter life
3. Collection of nanoparticles—thermal rebound of sub-10 nm particles

As for the first topic, nanofiber filters have attracted great attention because of the development of various manufacturing techniques of nanofibers (Choi et al., 2014; Choi et al., 2017; Xia et al., 2018). First part of this review will focus on the first topic. The second topic was recently reviewed by Kanaoka (2018), to which the readers of this review may refer. The third topic was first introduced by Wang and Kasper (1991) but the experimental verification and the quantification of thermal rebound effect on the filtration efficiency strongly rely on the development of a generation method of well-defined nanoparticles and a measuring method of sub-10 nm particles. The review on the third topic has to be done after the development of these techniques.

We may use air filters not only for the removal of particles but also for classification of particles by selecting an appropriate filter media by operating it under an optimized filtration condition for classification. Other topics introduced in the present review are the applications of filters and metal screen for aerosol classification and the use of centrifugal force for enhancing collection efficiency without increasing the pressure drop.
2. Filtration theory of virgin air filters

The mechanical collection mechanisms of air filters are Brownian diffusion, inertia, interception, and gravity. The relative contribution of each collection mechanism to the particle collection depends upon the physical properties of filter (fiber diameter, packing density, orientation of fibers and internal structure of filter), and particle properties (particle diameter, particle density, and the shape) as well as the filtration conditions (filtration velocity, pressure, and temperature) (Hinds, 1999; Stern et al., 1960; Wang et al., 2008). Fig. 1 shows the single fiber collection efficiency due to individual collection mechanisms as a function of particle size. As seen in Fig. 1, the collection efficiency curves due to individual collection mechanisms shift upward, i.e., an air filter becomes a higher performance filter with decreasing the fiber diameter.

HEPA filters composed of submicron fibers ($E > 99.97\%$ for $0.3\mu m$ particles) remove particles mainly by Brownian diffusion and interception, and the collection efficiency is affected by the internal structure of filter, such as the variance of fiber diameter, the inhomogeneity factor, and the packing density. Kirsch and Stechkina (1978) proposed the prediction method of HEPA filter based on the single fiber efficiency of Fan Model Filter (FMF) due to Brownian diffusion and interception. FMF is the filter in which monodispersed fibers are randomly packed and all of the fibers are placed perpendicular to the air flow. Since the inhomogeneity factor is defined as the ratio of pressure drop of FMF to that of a real filter at $Kn = 0$, non-uniformity of fiber diameter, orientation of fibers to airflow and uneven packing of fibers determine the inhomogeneity factor. Moreover, the slip flow effect on fiber surfaces becomes significant as the fiber size decreases. The single fiber collection efficiency of FMF accounting for the influence of slip flow is given by the following equations:

\[
\eta_f = \eta_D + \eta_R + \eta_{DR} \tag{1}
\]

\[
\eta_D = 2.7Pe^{-2/3} \left(1 + 0.39(K')^{1/3}Pe^{1/3}Kn\right) \tag{2}
\]

\[
\eta_R = \frac{1}{2K'f} \left(2(l + R)\ln(l + R) - (l + R) + \frac{1}{1 + R}
+ 2.86Kn \frac{(2 + R)R}{1 + R}\right) \tag{3}
\]

\[
\eta_{DR} = 1.24(K')^{1/2}Pe^{-1/2}R^{2/3} \tag{4}
\]

where $\eta_f$ is the single fiber collection efficiency of FMF, $\eta_D$ and $\eta_R$ are the diffusion and interception single fiber collection efficiencies, $\eta_{DR}$ is the interaction term for diffusion and interception. $Pe$ is the Peclet number defined by Eq. (5), $R$ is the interception parameter given by Eq. (6), $Kn$ is the Knudsen number defined by Eq. (7), and $K'$ is the hydrodynamic factor with the correction for slip flow given by Eq. (8):

\[
P_e = \frac{ud_f}{D} \tag{5}
\]

\[
R = \frac{d_p}{d_f} \tag{6}
\]

\[
Kn = \frac{2\lambda}{d_f} \tag{7}
\]

\[
K' = -0.5\ln\alpha - 0.52 + 0.64\alpha + 1.43(1 - \alpha)Kn \tag{8}
\]

where, $u$ is the filtration velocity (here, we define it as the interstitial velocity), $d_f$ the fiber diameter, $D$ the diffusivity of particles, $d_p$ the particle diameter, $\lambda$ the mean free path of air molecules, $\alpha$ the packing density of filter.

The pressure drop of an air filter is given by the following equation based on Darcy’s law:

\[
\Delta p = F\mu u_0 d_f \tag{9}
\]

where $F$ is the dimensionless drag, $\mu$ the viscosity, $u_0$ the superficial velocity and $l$ the fiber length in a unit filter area:

\[
l = \alpha L / \left(\frac{\pi d_f^2}{4}\right) \tag{10}
\]

The drag coefficient, $C_D$, is related to $F$ by the following equation:

\[
C_D = \frac{2F}{Re} = \frac{8\pi}{K'/Re} \tag{11}
\]

Fig. 1 shows the single fiber collection efficiency due to individual collection mechanisms as a function of particle size. As seen in Fig. 1, the collection efficiency curves due to individual collection mechanisms shift upward, i.e., an air filter becomes a higher performance filter with decreasing the fiber diameter.
where \( R_e \) is the Reynolds number and \( K' \) is the hydrodynamic factor given by Eq. (8).

For the prediction of collection efficiency of real fiber, Kirsch and Stechkina (1978) introduced the variance of dynamic factor given by Eq. (8).

\[
\sigma = \frac{d_t^2 - d_l^2}{d_l^2} = \exp[(\ln \sigma_g)^2] - 1
\]

(12)

\[
d_l = d_t = d_{ig} \exp[0.5(\ln \sigma_g)^2]
\]

(13)

\[
\delta = \left( \frac{\Delta P_f}{\Delta P_r} \right)_{K=0}
\]

(14)

where \( d_{ig} \) is the geometric mean diameter of fibers, \( \sigma_g \) the geometric standard deviation, and the superscripts \( f \) and \( r \) denote respectively “FMF” and “real”.

The filter efficiency, \( E \), is related to the single fiber collection efficiency of FMF by the following Eq. (15):

\[
E = 1 - P = 1 - \exp\left\{ - \frac{4}{\pi} \frac{\alpha}{(1-\alpha)(1+\sigma)} \frac{L}{d_l} \frac{\nu f}{\delta} \right\}
\]

(15)

The filter quality factor, \( q \), which is the measure of filter performance is defined by the following equation.

\[
q = -\ln P / \Delta P = \left( \frac{\eta_f}{C_\mu} \right) \frac{\mu_e}{(2/3) \mu^2} = \left( \frac{\eta_f}{C_\mu} \right) \frac{\rho_e}{(2/3) \mu^2}
\]

(16)

where \( \rho_e \) is the density of air. Fig. 2 shows the filter quality factor, which is calculated by using Eqs. (1)–(4) and (11) at \( u = 5 \) cm/s and \( \alpha = 0.06 \). As seen in this figure, \( q \) increases rapidly as the fiber diameter becomes smaller than 0.1 \( \mu m \), and reaches over unity at \( d_t = 10 \) nm. Fig. 2 is the reason that everybody tries to make fibrous filters with nanofibers.

![Filter quality factor as a function of fiber diameter.](image)

### 3. Nanofiber filters

Many researchers made efforts to fabricate air filters with low air resistance and high collection efficiency (Hung et al., 2011; Sambaer et al., 2012; Uppal et al., 2013; Cho et al., 2013; Hassan et al., 2013; Choi et al., 2014; Balgis et al., 2015; Wang et al., 2016; Zhang et al., 2016; Zhao et al., 2017; Choi et al., 2017). Most studies to fabricate nanofibers used an electrospinning process, which has a limitation of a low production rate. Only a couple of works used a melt blowing process, which fabricated micro- or nanofibers by blowing a polymer melt through a nozzle at a high speed (Uppal et al., 2013; Hassan et al., 2013).

Low pressure drop can be achieved by inducing slip flow around nanofibers. Several studies tried to prepare an air filter with low air resistance (Barhate and Ramakrishna, 2007; Hosseini and Tafreshi, 2010; Hung et al., 2011; Shou et al., 2014; Balgis et al., 2015; Bao et al., 2016; Zhao et al., 2016). Hung et al. (2011) fabricated Nylon 6 nanofibers ranging from 94 to 220 nm in diameter, and Balgis et al. (2015) made polyacrylonitrile nanofibers with diameter of 36.5–300 nm. However, they did not observe the reduction in pressure drop by slip effect. Zhao et al. (2016) claimed that those studies did not consider the optimal range of fiber diameter and the effective pore size. They fabricated PAN fibrous membranes with diameters between 53 and 168 nm by electrospinning and studied the effect of neighboring fibers on the pressure drop from both experiments and numerical simulations. They reported that the slip flow effect was found only under the very limited conditions, i.e., the fiber diameter between 60 to 100 nm and the effective pore size larger than 3.5 \( \mu \)m (Fig. 3). As shown in Fig. 3 the pressure drop at the filtration velocity of 5.3 cm/s is as small as 10 Pa, and the increase in pressure drop due to the decrease in fiber diameter from 71 to 53 nm is only 3 Pa, which is not significant and they obtained these data only at the filtration velocity of 5.3 cm/s and the particle size for the measurement of filtration efficiency was not specified. Moreover, the collection efficiency is as low as 45% at which the collection efficiency was determined mostly by the channeling flow through the pores and Brownian diffusion is not the dominant collection mechanism. In order to prove the effect of slip flow, the authors should have used fibrous membranes with different thicknesses and measured the collection efficiency and pressure drop at different filtration velocities and different particles sizes. Consequently, it seems the verification of slip flow effect on the filter collection performance still remains unresolved.

High collection efficiency for submicrometer particles can be attained by enhancing Brownian diffusion and interception, i.e., at a smaller Pelet number, \( Pe \), and a
larger interception parameter, \( R \), both of which results from a finer fiber (Podgorski et al., 2006; Wang et al., 2007; Yun et al., 2010; Wang et al., 2013; Choi et al., 2014; Bao et al., 2016). Choi et al. (2014) showed that submicrometer particles were effectively collected in a polyurethane nanofiber filter due to increased interception (in Fig. 4, particles ranging from 20 to 300 nm were evenly captured in a filter with the diameter of around 180 nm).

4. Application of air filters to aerosol classification

4.1 Inertial filter

The collection efficiency curve of an air filter is always concave against the axis of particle size as shown in Fig. 1, and the curves shift by changing the filter properties (fiber size, packing density, etc.) and the filtration conditions (filtration velocity, pressure, temperature, etc.). One extreme case is to use very high filtration velocity at which only inertia is the dominant collection mechanism and the collection of particles by diffusion is minimized. This is the case of inertial filter (Otani, et al., 2007). The measure of inertia is the Stokes number defined by:

\[
Stk = \frac{C_c \rho_p d_p^2 \nu}{9 \mu d_f}
\]

The representative length of a solid plate impactor is the diameter of the nozzle in the order of tens of micrometers, but for the inertial filter, it is the fiber diameter so that we can make \( Stk \) large enough to capture small particles at a relatively low air velocity through a nozzle. Fig. 5 shows the separation curves of a cascade impactor (Nanosampler, Kanomax, Model 3182) in which an inertial impactor stage was added downstream of the solid plate impactors. Since the inertial filter stage can separate submicron particles at the ambient pressure, we may have an additional fraction of particles in submicron size.
4.2 Sieving of aerosol particles by metal screen

We found out that the bounce-off of particles on the surface of fibers becomes significant at a high velocity even for submicron particles, which degrades the classification performance of inertial filter. Therefore, the cutoff size of particles upstream of inertial filter stage should be carefully designed in order to minimize the bounce-off of particles at the inertial filter stage. Such bounce-off phenomena are more significant when metal screen was used as a filter media. Recently, metal screens with uniform micrometer openings Metal Mesh Device (MMD, Murata Manufacturing Co., Ltd., see Fig. 6) were manufactured by a precision plating technique, and applied to the determination of PM$_{2.5}$ (Seto et al. 2014).

Although they obtained a good correlation between the mass of captured particles on the metal screen with 2.5 $\mu$m opening and that of PM$_{2.5}$, the mass of particles collected on 2.5 $\mu$m opening metal screen does not always reflect the mass of PM$_{2.5}$ because PM$_{2.5}$ are composed mostly of submicron particles. They obtained a good correlation probably because the particle size distributions were similar even when PM$_{2.5}$ concentrations were different. By combining these two previous works, we came up with an idea of “sieving of aerosol particles with metal screen.” If the bounce-off of particles is inevitable, we may enhance the particle bounce-off to achieve “no adhesion of particles.” If we could achieve “no adhesion of particles” onto metal screen, we may “sieve” aerosol particles by using uniform-opening metal screen solely by the geometrical sizes of particles.

Fig. 7 shows the collection efficiency of PSL particles through the metal screen with 2.5 $\mu$m opening at various filtration velocities (Kawara et al., 2016). The stepwise solid line in this figure is the ideal separation curve if there would be no particle adhesion on the metal screen. The collection efficiencies of 2.5 $\mu$m and 3.3 $\mu$m PSL particles are equal to unity at any filtration velocity, indicating that the metal screen can completely trap PSL particles larger than the mesh opening. At the filtration velocity of 0.6 m/s, as the particle size decreases, the collection efficiency of particles smaller than the mesh opening decreases discontinuously at the particle size equal to the mesh opening. At the filtration velocities of 3.0 and 10.6 m/s, the discontinuous drop in the collection efficiency at the particle size of mesh opening is more pronounced and the separation curve is very close to the ideal one.

Fig. 8 shows the collection efficiencies of PSL particles through the metal screens with 1.2, 1.8, 2.5, and 4.2 $\mu$m openings at the filtration velocity of 3.0 m/s. We can see from these figures that the collection efficiencies of particles larger than the mesh opening are equal to unity, indicating that we can completely trap particles larger than the mesh opening and that the cutoff size can be varied by changing the mesh opening.

Although the collection efficiencies of PSL particles smaller than the mesh opening are not equal to zero, i.e., we cannot completely suppress the adhesion of particles onto the metal screen, we can roughly “sieve” aerosol particles.
4.3 Centrifugal filter

One of the big drawbacks of air filter is such that we cannot change the collection efficiency once an air filter is installed when the filtration velocity is constant. Can we make the collection efficiency adjustable depending on the air quality, i.e., particle size distribution and concentration?

Nakajima et al. (2015) proposed a new type of filter named as “centrifugal filter” which collects aerosol particles by centrifugal force together with the conventional mechanical collection mechanisms so that the centrifugal filter can adjust the collection efficiency by changing the rotation speed (Fig. 9).

The attempts to combine centrifugal force and mechanical collection mechanisms were made previously and there are commercially available rotary filters (Sintokogio, Ltd. 2015). The biggest difference between the centrifugal filter proposed by the authors and the conventional rotary filters is such that in the centrifugal filter the centrifugal force exerts particles in the direction perpendicular to the airflow. In the conventional rotary filters, the centrifugal force exerts parallel to the airflow and the targeted particle size of collection is mostly several tens of micrometers. By letting the centrifugal force act perpendicular to the airflow, the centrifugal filter possesses many advantages over the conventional ones, i.e., depth filtration with a long residence time of particles in the filter, and no shedding of particles into the filtered air.

Fig. 10 shows the collection efficiencies of centrifugal filter against the particle diameter at the fixed filtration velocity, $u = 2.5 \text{ cm/s}$. SUS fiber filter with diameter, $d_l = 50 \mu \text{m}$, was used as a filter media. As shown in the

![Fig. 8 Separation curve of metal screens with various openings at filtration velocity of 3 m/s.](image_url)
The collection efficiency without rotation (blue squares) is smaller than 10% at the MPPS (most penetrating particle size) which is about 1 μm. The collection efficiency of particles larger than 0.5 μm is significantly improved by rotating the filter. At the maximum rotation speed of 3,000 rpm, the collection efficiency of 1 μm PSL particles increases to 90%.

Fig. 11 shows the pressure drops of centrifugal filter consisting of fibers with different diameters as a function of rotation speed at a fixed filtration velocity of 2.5 cm/s. The fiber diameter is larger than 10 μm so that there is no additional pressure drop to that of filter holder and you can find that the increase in pressure drop due to filter rotation is not significant. The small increase in pressure drop by rotating the filter is explained as follows. When the filter rotates, the air embedded in the filter also rotates with the fiber media. Therefore, no relative motion in the circumferential direction of filter rotation between the air and fibers would be added, and therefore the pressure drop is determined mostly by the relative motion between the air and fibers in the axial direction of flow. Consequently, the rotation of filter contributes mostly to the enhancement in collection efficiency while keeping the pressure drop as small as that of static filter.

Since the collection efficiency of the centrifugal filter is adjustable just by changing the rotation speed, it was successfully applied to classify different sizes of particles by scanning the rotation speed followed by the detection of filtered aerosol by a photometer in order to measure the size distributions (Tanaka et al., 2017). The measurable size range overlaps the range of optical particle counters and the centrifugal filter can give the size distribution based on the aerodynamic size.

5. Conclusion

Air filters have been used to obtain clean air but they may have other applications of particle classification by tuning the collection efficiency curve by adjusting filter properties and filtration conditions. The inertial filter is one of the examples in which particles are collected solely by inertia so as to make the filter as the inertial classifier. At a very high filtration velocity, we may use metal screen as a sieve for aerosol by suppressing the adhesion of particles. The centrifugal filter is another example to make air filter as an aerosol classifier with variable cutoff sizes.

Air filters have varieties of applications, more than we can think of, because any porous media can be used as a filter medium and we may use it under extreme filtration conditions and combine it with various external force fields. With the development of various techniques for manufacturing fibers and porous media, now is the time to think about new applications of air filters.

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References

Bao L., Seki K., Niimura H., Otani Y., Balgis R., Ogi T., Gradon L., Okuyama, K. Verification of slip flow in nanofiber filter media through pressure drop measurement at low pressure


Xia T., Bian Y., Zhang L., Chen C., Relationship between pressure drop and face velocity of electrospun nano fiber filters, Energy Build., 158 (2018) 987–999.


Zhao X., Wang S., Yin X., Yu J. Ding B., Slip-effect functional air filter for efficiency purification of PM2.5, Scientific Reports, 6 (2016) 35472. DOI: 10.1038/srep35472
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