Initial Collection Efficiency of Electret Filter and Its Durability for Solid and Liquid Particles†

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Abstract

Expressions to describe the initial collection efficiency of electret filters for both charged and neutral particles were derived covering a wide range of Coulombic force and induced force parameters including the interceptional effect. The prediction equations were in good agreement with the experimental data. Further, the electret charge stability in humid air and in exposure to liquid and solid particles was studied by measuring the time dependency of the particle penetration. It was found that the electret charge is quite stable in humid air but that it is gradually attenuated when exposed to organic droplets because the collected organic droplets spread over the fibers and weaken the electric field around them.

Introduction

An electret filter consists of semi-permanently charged fibers and has a higher collection efficiency compared to its mechanical counterpart due to strong electrostatic attraction between particles and fibers.

The initial collection efficiency of an electret filter with a uniform charge distribution on each fiber was theoretically studied by Natanson61 and Pich7. For the electret fiber with a charge distribution as shown in Fig. 1, Brown3 derived expressions for the collection efficiency due to Coulombic and induced forces, and Pich8 proposed a prediction equation for the Coulombic force including the interceptional effect. However, Brown’s prediction equation did not include the interceptional effect for a large interception parameter, which is important in the filtration of relatively large particles with fine electret fiber, while Pich’s equation did not specify the range of the interception parameter for which his equation is applicable, although there is a critical interception parameter below which the interception effect is negligible.

This paper proposes useful prediction equations which cover the practical range of Coulombic and induced force parameter accounting for the interceptional effect. Further, since the stability of the electret charge is of great consideration for practical use, the charge stability was studied when an electret filter is exposed to organic mist and dust particles as well as to particle-free humid air.

1. Initial collection efficiency

1.1 Charged particles

For an electret filter with a dipole charge as shown in Fig. 1, Brown introduced a particle stream function and theoretically obtained the following expression of single fiber collection efficiency for charged particles when the interception effect is negligible.

\[
\eta_c = 0.59 h_0^{0.17} K_c^{0.83}
\]  

(1)
Where $h_K$ is the hydrodynamic factor given by Eq. (2) for the Kuwahara flow, and $K_c$ the Coulombic force parameter defined by Eq. (3).

\[
h_K = -0.51n_0 \alpha + \alpha - \alpha^2 - 0.75 \tag{2}
\]

\[
K_c = \frac{C_{en} \varepsilon_0}{6 \varepsilon_0 (1 + \varepsilon_0) \mu d_{\mu u}} \tag{3}
\]

In electret filtration as opposed to mechanical filtration, the limiting trajectory of particles is such that the particles pass through a point at which their velocity is zero. Therefore, a particle with a limiting trajectory is transported toward the fiber surface in a direction normal to the fiber from the zero-velocity point and then collides with the surface where it is finally collected. Consequently, interception plays no role when a particle’s radius is smaller than the distance between the zero-velocity point and the fiber surface. This implies the existence of a critical value for the interception parameter below which interception does not affect the single fiber collection efficiency. Brown showed that, for the collection of charged fibers, this critical interception parameter depends upon the orientation angle of the electret dipole $\gamma$ and that interception is completely negligible for $R < (K_c h_K/2)$ while for $R < (K_c h_K)^{1/2}$ it is important at some value of the angle $\gamma$.

Pich et al.\(^6\) derived the following expression for the Coulombic and interception single fiber efficiency at a fiber orientation $\gamma$, by assuming that a particle with a limiting trajectory has a zero tangential velocity at a half particle diameter away from the fiber surface.

\[
\eta_{CR} = \left\{ \eta_R + \frac{K_c^2}{(1 + R)^2} - \frac{2\eta_R K_c}{1 + R} \cos \gamma \right\}^{1/2} \tag{4}
\]

where $\eta_R$ is the interception efficiency which is given for the Kuwabara flow as follows.

\[
\eta_R = \frac{1}{2h_K} \left\{ \frac{1}{1 + R} - (1 + R) \right. \\
+ \left. 2 (1 + R) \ln (1 + R) \right\} \tag{5}
\]

Further, they obtained the average single fiber efficiency by integrating the above equation over all dipole orientations assuming that a dipole orientation is random in the filter.

\[
\bar{\eta}_{CR} = \eta_R + \left\{ \frac{1}{1 + R} - \frac{\eta_R}{(1 + R) \eta_R + K_c} \right\} K_c \tag{6}
\]

Fig. 2 compares the Coulombic single fiber efficiency obtained by the particle trajectory calculation according to Brown’s paper ($R = 0, \gamma = \pi/2, \alpha = 0.05$) with that obtained by Eq. (4). Since Pich’s equation does not account for the existence of a critical interception parameter, there is a contradiction in that the single fiber efficiency is higher for a smaller interception parameter in a large $K_c$ region. Fig. 2 shows that the single fiber efficiency curve obtained by Brown’s procedure is an envelope of the curves calculated by Eq. (4). The critical interception parameter $R_c$ which was calculated by the authors according to Brown’s procedure is shown in Fig. 3 as a function of $K_c$ and $\gamma$, and the values of $K_c$ which give the critical interception parameter of $R_c = 0.05, 0.1, 0.2, 0.5$ at $\gamma = \pi/2$ are plotted by
solid circles in Fig. 2. It can be seen that the curve obtained by the Brown's procedure is tangent to the curves predicted by Pich's equation at points of solid circles. Therefore, Pich's equation Eq. (4) is valid only for \( R > R_C \) while for \( R < R_C \) it is necessary to apply Brown's procedure to calculate the single fiber efficiency.

Fig. 2 is a comparison for the dipole orientation \( \gamma = \pi / 2 \). However, because the orientation of a dipole charge in an electret filter is random, it is necessary to use a single fiber efficiency averaged over all the orientations of the dipole charge to calculate the filter efficiency. Fig. 4 compares the average single fiber efficiencies predicted by Eqs. (1) and (6). In this figure, since the applicable range of the Coulombic force parameter of Eq. (1) is not clearly given by Brown, the single fiber efficiency was recalculated by the authors for \( 0.01 < K_C < 5 \) at \( \alpha = 0.05 \). Unlike Fig. 2, the curve predicted by Brown's procedure is not an exact envelope of Pich's curves in Fig. 4. For the average single fiber efficiency, it is futile to consider the critical interception parameter because it varies with the dipole charge orientation. Nevertheless, the single fiber efficiencies at the Coulombic force parameter which gives the critical interception parameter at \( \gamma = \pi / 2 \) (shown by solid circles) are fairly close to those predicted by Brown's curve. Therefore, in the prediction of the single fiber efficiency, to calculate the filter efficiency, we may use the critical interception parameters at \( \gamma = \pi / 2 \) as the limit of the applicable range of Eq. (6). Consequently, since the critical interception parameter at \( \gamma = \pi / 2 \) shown in Fig. 3 is approximated by \( R_C = 0.66 \) \((K_C h_R)^{0.64}\), for \( R > R_C \), Eq. (6) may be used for the average single fiber efficiency, and for \( R < R_C \), the following equations which are approximations of the equation of Brown's curve shown in Fig. 4 must be used.

\[
\bar{\eta}_C = 0.78 K_C^{-1} ; 10^{-3} < K_C < 10^{-1}
\]

\[
\bar{\eta}_C = 0.59 h_K^{0.12} K_C^{0.83} ; 0.1 < K_C < 10
\] (7)

1.2 Neutral particles

Neutral particles are polarized by the electret charge and collected on the electret fibers as a result of the attractive force existing between the charge induced on the particles and the electret charge. The induced force is a function of only the distance between a particle and the electret fiber and does not depend on the dipole charge orientation. Therefore, the limiting trajectory always ends at the rear stagnation point of the fiber (\( \theta = 0 \)). By making use of this, Brown analytically obtained a point on the \( \theta = 0 \) axis at which the particle velocity is zero, and numerically traced the particle trajectory backwards to obtain the original position of particles upstream the fiber.

The prediction equation derived by Brown for neutral particles is given by the following equation.

\[
\bar{\eta}_n = 0.54 h_K^{0.60} K_n^{0.40} \text{ for } 1 < K_n < 100
\] (8)

where \( K_n \) is the induced force parameter defined by

\[
K_n = \frac{(E_p - 1) C_p \bar{\sigma}_n^2 d_p^2}{6 (E_p + 2) \bar{\epsilon}_0 (1 + \bar{\epsilon}_p)^2 \mu d u}
\] (9)

Likewise for charged particles, there exists a critical interception parameter in the collection of neutral particles. The critical interception parameter given by Brown is as follows.

\[
R_C = (h_R K_n)^{1/2}
\] (10)

We recalculated the single fiber efficiency using Brown's procedure for a small \( K_n \) region accounting for the interceptional effect and the results were compared with the curves predicted by Eq. (8) and Natanson's equation \( (\bar{\eta}_n = \pi K_n) \). The present calculation results of the single fiber efficiency for \( R = 0 \) coincide with Natanson's in a small \( K_n \) region and with Brown's for \( K_n > 1 \). Incidentally, the values for \( K_n \) at which the present results of single fiber efficiency with interception equal to those
without interception (R = 0), correspond to those predicted by Eq. (10). The single fiber collection efficiency due to the induced force at R = 0 can be expressed by the following equation.

\[
\eta_{\text{In}} = 1.48 K_{\text{In}}^{-0.93} ; 10^{-4} < K_{\text{In}} < 10^{-2}
\]

\[
\eta_{\text{In}} = 0.51 h K_{\text{In}}^{0.73} ; 10^{-2} < K_{\text{In}} < 1
\]

\[
\eta_{\text{In}} = 0.54 h K_{\text{In}}^{0.40} ; 1 < K_{\text{In}} < 100
\] (11)

**Fig. 5** Collection efficiencies of a single electret fiber due to induced force.

1.3 Comparison with the experimental data
To confirm the validity of the prediction equations derived above, measurements of the collection efficiencies of electret filters were carried out by using the experimental set-up shown in **Fig. 6**. Liquid particles of DOS (Diocylsebacate) were used as a test aerosol. DOS droplets were generated by a evaporation and condensation type aerosol generator and classified into monodisperse particles with a DMA (differential mobility analyzer). Following the classification of the particles by size, their charging state was regulated by a combination of a bipolar charger, a unipolar charger, the DMA and a parallel plate condenser to obtain uncharged, multi-charged, and uncharged particles. The test filters used in the experiments were electret filters consisting of polypropylene fibers with a diameter of 1.3 µm, a filter thickness of 0.71 mm and a packing fraction of 0.0612.

**Fig. 7** shows the influence of the fiber and particle charges on particle penetration. The particle penetration of uncharged particles through an uncharged filter (designated by P_{\text{Un}} in **Fig. 7**) was obtained by using an uncharged filter having the same filter property as an electret filter. When neutral particles are collected by an uncharged filter, the particle penetration curve is convex against the particle diameter because interception is dominant for large particles while there is a Brownian diffusion for small particles. When the filter is charged, the induced force acts on the neutral particles, and thus the particles' penetration decreases with increasing particle diameter. When both filter and particles are charged, the Coulombic force is responsible for the collection of small particles and the induced force for that of large particles, resulting in low particle penetration in an entire particle size region. By assuming the additivity of the collection efficiencies due to the two individual mechanisms, the single fiber
collection efficiency due to the induced force was calculated using Eq. (12) and is plotted against the induced force parameter $K_{1n}$ in Fig. 8.

$$\eta_{In} = \eta_{InM} - \eta_M = -\frac{\pi}{4} \frac{1 - \alpha}{\alpha} \left( \frac{d_f}{L} \right) \ln \left( \frac{P_{InM}}{P_M} \right)$$  \hspace{1cm} (12)

In Fig. 8, since the charge on the electret filter used in the present work is unknown (actually, the measurement of the electret charge was attempted by Baumgartner et al.\textsuperscript{2}), however, it is very difficult to obtain the average charge for an electret fiber with a charge distributed along the fiber length), the electret charge is assumed to be $\bar{\sigma} = 5.1 \mu C/m^2$ in order to satisfy the theoretical equation Eq. (11). Although the data scatter in the region of small $K_{1n}$, most of the data fit a single curve as predicted by Eq. (11), indicating that Eq. (11) is applicable for the prediction of the single fiber efficiency due to the induced force.

Fig. 9 shows the single fiber efficiency due to the Coulombic force as a function of the Coulombic force parameter. The single fiber efficiency was calculated using Eq. (13) by assuming the additivity of single fiber efficiencies due to the induced force and the Coulombic force.

$$\eta_C = \eta_{InCM} - \eta_{InM} = -\frac{\pi}{4} \frac{1 - \alpha}{\alpha} \left( \frac{d_f}{L} \right) \ln \left( \frac{P_{InCM}}{P_{InM}} \right)$$  \hspace{1cm} (13)

Since the electret charge is not measurable as in the case for the induced force parameter, the value of $\bar{\sigma} = 5.1 \mu C/m^2$ which was obtained from the data for neutral particles was used to calculate the Coulombic force parameter. It can be seen from Fig. 9 that experimental data are well expressed by Eq. (7).

What follows from the comparison between experimental data and the prediction equations is that the assumed value for the electret charge $\bar{\sigma} = 5.1 \mu C/m^2$ is true and that these prediction equations are valid for use to obtain the average single fiber efficiencies due to the induced force and the Coulombic force.

2. Stability of electret charge

As shown in the preceding section, the electret filters have a very high initial collection efficiency compared to the conventional mechanical filters because the induced force and/or Coulombic force as well as the mechanical collection mechanisms, such as interception and Brownian diffusion, act on the particles. However, since the electret charge is not infinitely permanent, the problem arises on how long the initial collection efficiency is maintained for practical use. In the following sections, the electret charge stability is discussed when it is exposed to humid air and liquid and solid particles.

2.1 Influence of humidity

Because electret filters have a dipole charge on the fibers, the charge may be neutralized by a charge...
transfer through the fiber or along the fiber surface. If the charge disappears by the surface charge transfer or is neutralized by the adsorption of ions on the fiber surface, humidity may greatly affect the charge decay characteristic of the electret filter. Fig. 10 shows the time course of particle penetration through the electret filter when the electret filter is exposed to particles-free humid air. As shown in the figure, the particle penetration remains constant for over a month, indicating that the electret charge is quite stable in humid air. Therefore, it can be said that the charge decay due to surface or volume conduction of dipole charges is negligible.

2.2 Influence of captured particles

Baumgartner and Löffler\(^1\) reported that particles collected in an electret filter lead to two opposing effects; i.e., an increase in collection efficiency due to the increased interception effect by the captured particles, and a collection efficiency decrease due to neutralization of the electret charge. Since the extent of these effects changes with the fiber size and the morphology of the particles accumulated in the filter as well as the particle load on the filter, particle penetration varies in a complex manner with the particle load. Fig. 11 compares the time dependency of penetration of charged liquid particles with that of charged solid particles. 0.1 \( \mu \)m DOS particles and 0.1 \( \mu \)m iron alum particles classified by the DMA were used as a test aerosol. Since the fiber size of the electret filter is as small as 1.3 \( \mu \)m, particle penetration of solid particles gradually increases with the particle load since the increased interception effect counterbalances the decrease of the electret charge. On the other hand, the penetration of liquid particles decreases with the particle load because captured droplets spread over the fibers contributing to a weakening of the electric field around the fiber without increasing the interceptional effect.

The difference in the morphology of the particles accumulated in the electret filter is also inferred from the pressure drop change with the particle load, i.e., the solid particles clog the filter pores thus increasing the filter pressure drop, whereas the pressure drop is almost constant when liquid particles are filtered.

The reason for the particle penetration increase in the charged liquid particle filtration may be attributed to the neutralization of the electret charge by the opposite particle charge and the weakening of the electric field around the fibers due to the fiber surface being covered with a liquid layer. The influence of the latter on the electret filtration can be found by measuring the penetration of neutral droplets. Fig. 12 shows the comparison of neutral droplet penetration.
compares the penetrations of neutral and uni-charge droplets through an electret filter. This figure shows that there exists a gradual increase in the penetration of neutral particles although it is not as significant as that of uni-charged particles. Therefore, even for neutral droplets, a decrease in collection efficiency occurs due to the fiber surface being covered with a liquid layer.

Fig. 13 shows the comparison of single fiber efficiencies for neutral and uni-charged droplets. The abscissa in the figure is the amount of particles collected in the filter calculated using the following equation.

\[ m = \frac{1}{L} \int_{0}^{C_{\text{ut}}} E_{\text{d}} (C_{\text{ut}}) \, dt \]  

(14)

As can be seen from the figure, the single fiber efficiency for neutral particles decreases with particle accumulation and becomes equal to that of uncharged fibers at about \( m = 0.5 \, \text{kg/m}^3 \). From the data for neutral particles, the charge on the electret fiber with particle accumulation was estimated by using Eq. (11), and this charge was used to calculate the single fiber efficiency for charged particles. The predicted change in single fiber efficiency for charged particles is also shown in Fig. 13. The predicted single fiber efficiency curve expresses the trend of experimental data fairly well, suggesting that the covering of the fiber surface with a liquid layer is the main cause of penetration increase even for charged droplets.

**Conclusion**

Prediction equations of electret fiber collection efficiency were derived for a relatively small electrostatic interaction between particles and electret fibers accounting for the interception effect, and compared with the experimental data. Further, the stability of the electret charge was experimentally studied when the electret filter was exposed to liquid and solid particles as well as to particle-free humid air. Consequently, it was found that the electret charge is fairly stable in humid air, but that the collection efficiency for liquid droplets gradually decreases with the particle load on the filter because captured droplets covered the fiber surface and thus weakened the electrical field around the fibers. Since the covering of the electret fiber surface with a liquid layer is dependent on the wetting property of the liquid, special attention is required in the electret filtration of organic droplets.

**Nomenclature**

- \( C_{\text{C}} \) = Cunningham's slip correction factor
- \( d_{\text{f}} \) = Fiber diameter [m]
- \( d_{\text{p}} \) = Particle diameter [m]
- \( E \) = Collection efficiency of filter [-]
- \( e \) = Elementary charge [C]
- \( h_{\text{K}} \) = Hydrodynamic factor [-]
- \( K_{\text{C}} \) = Coulombic force parameter defined by Eq. (3) [-]
- \( K_{\text{ln}} \) = Induced force parameter defined by Eq. (9) [-]
- \( L \) = Filter thickness [m]
- \( m \) = Accumulated mass of particles [kg/m³]
- \( n_{\text{p}} \) = Number of charges on a particle [-]
- \( P \) = Particle penetration through filter [-]
- \( R \) = Interception parameter \( (\frac{d_{\text{p}}}{d_{\text{f}}}) \) [-]
- \( R_{\text{c}} \) = Critical interception parameter [-]
- \( r \) = Radial distance [m]
- \( t \) = Filtration time [s]
- \( u \) = Filtration velocity [m/s]
- \( \alpha \) = Packing density of fibers [-]
- \( \gamma \) = Angle of dipole charge to airflow [-]
- \( \varepsilon_{\text{O}} \) = Space permittivity \( [\text{C}^2/(\text{Nm}^2)] \)
- \( \varepsilon_{\text{d}} \) = Dielectric constant of fiber [-]
- \( \varepsilon_{\text{p}} \) = Dielectric constant of particle [-]
- \( \eta \) = Single fiber collection efficiency [-]
- \( \bar{\eta} \) = Average single fiber collection efficiency [-]
### Subscripts

- **C**: Coulombic force
- **In**: Induced force
- **i**: Inlet
- **M**: Mechanical
- **R**: Interception

### Literature cited