The effect of electrostatic forces on filtration efficiency of granular filters

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A B S T R A C T
The effect of electrostatic forces on the granular filtration of nanoaerosol NaCl particles in the range of 10 nm to 100 nm was investigated experimentally in this study. The test granular filters were made of 2 mm homogeneous glass beads at three media thicknesses (25, 76 and 127 mm), and they were tested at three air flow rates (27, 45, and 65 lpm). The filtration efficiencies were measured for neutralized and charged NaCl nanoparticles. The corresponding difference was considered as the filtration efficiency attributed to the electrostatic attraction between the charged NaCl particles and the glass granules. Results showed that the electrostatics played a great role in nanoaerosol filtration, which is different from conventional filtration theories. Its contribution to filtration efficiency increased with the size of the nanoparticles to a level of 30% or so. Results also showed a positive correlation between the separation efficiency due to electrostatic forces and the residence time of the air flow. The correlation is relatively strong (between 0.6 and 0.9) for particles in the range of 20–100 nm. However, it is weak, although positive, for sub-20 nm particles.

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1. Introduction
Clean air is a vital resource for human life. However, population growth, enhanced human activities, and the rapid expansion in industrial production have led to unprecedented demand on clean air all over the world. The report of the World Health Organization (2013) showed that over seven million premature deaths each year are attributed to air pollution. Among the air pollutants, nanosized aerosol (nanoaerosol) particles suspended in the air are proven to cause adverse impact on human health. In addition, they also negatively impact on global climate change and extreme weather by interacting with the solar radiation. It is important to capture the nanoaerosol particles, at their sources and from the ambient air.

Among all of the technologies for removing nanoaerosol particles from their carrier gases, air filtration is the simplest and most widely used method. A great amount of works have been conducted with fibrous filters, membrane filters and fabric filters [1–3]. However, much less attention has been paid to granular air filtration. Limited information has shown that granular air filtration has high removal efficiency for a wide range of particle size [4–8]. Granular filters may also be the only and promising option for air filtration at high temperature and high pressure [8–13].

The mechanisms of granular air filtration are similar to those of fibrous air filtration, except that the particles are deposited on surfaces of the granules. Among all the particle transport mechanisms, it has been widely accepted that diffusion is the dominant mechanism for removal of nanoparticles (1–100 nm in diameter), and the electrostatic effect is often ignored in conventional air filtration models that were developed based on single fiber theory [14,15], it is not certain for granular filtration. Aerosol particles and granules often carry electrostatic charges which may influence particle transport, and the consequent removal efficiency. The electrostatic forces between particles and granules may include image forces, dielectrophoresis due to collector charge, columbic force, space charge effect, columbic force due to external field, and dielectrophoresis due to external electric field. However, the columbic force due to particle charge and an external electrostatic field are the most dominated forces [16].

Several researchers have employed external electric field in granular filtration to enhance the particle removal efficiency [17]. The external electric field causes the granular beads to polarize. In this case, either neutral or charged particles are attracted to the polarized granules, leading to increased filtration efficiency. Particles travel a shorter distance in granular filters than in a conventional electrostatic precipitator to reach the collector surface. And, the collection surface area per volume of granules is larger than that of an electrostatic precipitator; therefore, the electrostatic attraction effect is likely to increase the collision chance of particles and consequently filtration efficiency [18].

Although a number of studies have been conducted by considering external electric field to enhance electrostatic forces between microsized particles and granular beads, there is very limited information about the effect of electrostatic forces on granular filtration of nanoparticles. In this work, experiments were carried out to investigate the effect of electrostatic forces on nanoaerosol filtration. The granular filters tested were made of uniform 2 mm glass beads at three media thicknesses of 25, 76 and 127 mm, and they were tested at three flow
rates of 27, 45 and 65 lpm. The feed aerosol contained NaCl nanoparticles in the range of 10–100 nm.

2. Theoretical

The fractional filtration efficiency of a granular filter can be correlated with the single granule efficiency as [17]:

$$
\eta = 1 - \exp \left( -\frac{3}{2} \frac{(1-\epsilon)}{\epsilon} \left( \frac{L}{d_g} \right) \right)
$$

(1)

where $d_g$ is the granule diameter, $L$ is the filter bed thickness, $\epsilon$ is the filter bed porosity, and $\eta_0$ is the single collector efficiency of the granular. The filter bed porosity of the filter is defined as follows [19]:

$$
\epsilon = 0.375 + \left( \frac{D}{d_g} \right)^{-2} \text{ for } \frac{D}{d_g} > 2, \ L > 20d_g
$$

(2)

where $D$ is the body diameter of the granular bed.

The single granule efficiency for nanoparticles based on diffusion and electrostatic attraction is defined as follows:

$$
\eta_0 = 1 - (1 - \eta_0)(1 - \eta_k)
$$

(3)

where $\eta_0$ and $\eta_k$ are single granular efficiency due to Brownian diffusion and electrostatic forces, respectively. Tufenkji and Elinelech [20] developed a model to calculate Brownian diffusion based single collector efficiency for each particle size as follows:

$$
\eta_0 = 2.4 A^1 \left( \frac{d_p}{d_g} \right)^{-0.861} Pe^{-0.715} N_{vdw}^{0.052}
$$

(4)

where $d_p$ is the particle diameter, $d_g$ is the granular size, $A$ is the porosity dependent parameter, $Pe$ is the Peclet number, and $N_{vdw}$ is the van der Waals parameter. $A$ is defined as follows:

$$
A = \frac{2 - 2(1-\epsilon)^3}{\left[ 2 - 3(1-\epsilon)^2 + 3(1-\epsilon)^3 - 2(1-\epsilon)^2 \right]^2}
$$

(5)

The Peclet number is defined as

$$
Pe = \frac{d_p U}{D_i}
$$

(6)

where $D_i$ is the particle diffusion coefficient and $U$ is the superficial velocity. The van der Waals parameter is given by:

$$
N_{vdw} = \frac{A_{vdw}}{kT}
$$

(7)

where $A_{vdw}$ is the Hamaker constant of interacting media (particles and granules). The Hamaker constant for glass beads is 0.85 × 10⁻¹⁹ J and that for NaCl particles is 0.79 × 10⁻¹⁹ J.

When charged particles pass through the granular filters, the single collector efficiency is enhanced by the electrostatic attraction. The charge states of particles and granules should be known in order to calculate the electrostatic forces. The calculation of single collector efficiency based on electrostatic forces needs complex trajectory analysis. For simplicity, Deutsch equation that was primarily developed for standard ESPs is employed. In this model, the electric field strength in granular filters is defined as the field induced by the net charge on the glass beads and aerosol particles [21]. The single granule efficiency due to electrostatic force is then defined as [22]

$$
\eta_k = 1 - \exp \left( \frac{-2(1-\epsilon)Lq_P C_e E}{\pi \mu Ud_g d_p} \right)
$$

(8)

where $q_p$ is the particle charge, $C_e$ is the slip correction factor, and $E$ is the electric field strength. Eq. (8) shows that the single collector efficiency depends on the charge state of particles, glass beads, and the electric field intensity. If the particles are charged to saturation, the maximum charge can be calculated as follows.

$$
q_p = \frac{d_p K_B T}{2 e K_c} \ln \left( 1 + \frac{d_p K_c e^2 N_i t}{2 K_t} \right)
$$

(9)

where $c_i$ is the mean thermal speed of ions, $K_B$ is Boltzmann constant, $K_c$ is Coulomb’s constant of proportionality, $e$ is the electrocharge, and $N_i$ is the ion concentrations in the order of 5 × 10¹⁴ ions/m³ [23].

3. Experimental setup

Fig. 1 shows the experimental setup for measuring the removal efficiencies of the granular filters. A constant output atomizer (TSI model 3076) was used to generate polydisperse sodium chloride (NaCl) nanoparticles. The concentration of sodium chloride in the distilled water was 0.1 g/l as recommended by the manufacturer. A diffusion dryer (TSI model 3062) was used after the atomizer to dry the highly charged particles. Note that all aerosol particles carry charges after exiting the atomizer [24]. When these nanoparticles pass through the 20-mCi Po-231 neutralizer (NBD), the ions on the particles are neutralized and acquire Boltzmann equilibrium charge distribution. Without using the neutralizer, the charges on the nanoparticles cause electrostatic forces between the particles and filter collectors.

Fig. 2 shows the schematic diagram of the cylindrical granular filter, which was the same as the one used by Golshahi et al. [4]. Air flow entered the filter from the bottom of the bed in a counter-current flow mode. There was a fixed height of 9 cm between the base of the filter unit and the level where the gas first interacted with the granules (h = 0). This fixed thickness below h = 0 was used to slow down the gas flow and it acted as a flow conditioner.

The granular bed properties are shown in Table 1. Glass beads with the uniform diameter of 2 mm in combination with three bed thicknesses (2.5, 7.6 and 12.7 cm) were used. The packed bed was purged for an hour prior to each experiment to allow the system to reach a steady state. Glass beads usually carry negative ions because of the free electrons in the air [25]. While it is difficult to quantify the exact charges on the glass beads, it is expected to be profound when the air is pretty dry (RH ≤ 20%) in Calgary, Alberta, Canada. All the experiments were tested at room temperature (T = 23 °C) to reduce the effect of temperature.

A thermal mass flow meter (TSI model 3063) meeting the criteria of the isokinetic sampling measured the main stream flow rate. A dust collector was used to make the system under vacuum condition and an opening was added after the aerosol generator to balance the air pressure in the system.

A scanning mobility particle sizer (SMPS) consisting of a long differential mobility analyzer (DMA) (TSI model 3081) and a condensation particle counter (CPC) (TSI model 3775) was employed to determine the size distributions of particles. DMA was tuned for classifying particles in the range of 5.76 nm to 239 nm by adjusting the impactor nozzle to 0.075 cm. CPC was used to detect nanoparticles down to 4 nm in the range of 0 to 10⁷ particles/cm³. The shear air flow to the sampling air flow was remained constant to 10, during all experiments.

The system was used both upstream and downstream the granular filters to determine the concentrations of particles before and after the
granular filter. The fractional filtration efficiency of the granular filter is calculated by

\[ \eta = \frac{C_{\text{in}} - C_{\text{out}}}{C_{\text{in}}} \times 100\% \]  

where \( C_{\text{in}} \) is the upstream particle concentration and \( C_{\text{out}} \) the downstream particle concentration. Both concentrations were measured at the inlet and the outlet of the granular bed. The removal efficiencies of granular filtration for nanoparticles were calculated by considering the average of three replications with the standard deviation of less than 2%.

The aerosol particle removal efficiencies were measured with and without employing the neutralizer by maintaining other factors constant. The difference between the filtration efficiency for charged and neutralized particles is attributed to the effect of electrostatic forces between charged particles and granular glass beads. It is deemed reasonable because it is the only factor that changes in the test for a certain particle size.

4. Results and discussion

Fig. 3 shows the filtration efficiencies due to electrostatic force only. All the results show that the filtration efficiency by electrostatic attraction increased with particle size. The filtration efficiency by electrostatic attraction could increase to 20–30% when the particle diameter increased to 100 nm. This effect is much more profound that any other researchers reported in the past [2,26]. Almost all of other researchers concluded that the filtration efficiencies due to electrostatic forces are negligible for nanoparticles. For example, the study on the electrosprun filter for sub-80 nm NaCl particles showed that the nanoparticle removal efficiency is independent of charge state of particles, which showed the negligible effect of cinematic force compared to the strong diffusive force [26,27]. On the other hand, Kim et al. [2] showed that the filtration efficiency of sub-100 nm sodium chloride particles is lower for uncharged particles than for charged particles at face velocity of 2.5 cm/s, and this discrepancy decreases with the decrease in the particle size. However, the discrepancy in their study is much lower than those shown in Fig. 3. The difference is likely related to differences in filter type and filter media.

4.1. Effect of particle size on electrostatic force

First of all, the filtration efficiency of sub-20 nm particles due to electrostatic attraction is negligible for most cases in Fig. 3, and even a closer examination shows the negative effect for most sub-20 nm particles. Therefore, the filtration efficiency of sub-20 nm particles is still dominated by diffusion. This agrees with conventional theory because of extremely small amount of ions that these small particles can be carried.

However, this may not be the case of larger nanoparticles. The filtration efficiency due to electrostatic forces increases to a maximum level of 30–35% when particle size increased to 100 nm. Results showed that the filtration efficiency of nanoparticles enhance if the neutralizer is not used, i.e. by the effect of electrostatic force. As most of nanoparticles generated by atomizer may carry positive ions and the attraction force between positive particles and the negative glass beads is the dominant reason for the increase in the filtration efficiency.

One of the most important factors that contribute to the size dependent performance is the size-dependent charging and neutralization on nanoaerosol particles. First of all, although all aerosol particles carry charges after exiting the atomizer, there are only single ions (positive or negative) on the sub-20 nm particles. It is not enough to produce strong electrostatic forces. As indicated by Eq. (9), larger particles can acquire more charges leading to greater electrostatic forces in the same electrical field.

For nanoaerosol particles the analytical solution of the transient charging equation has been obtained following the Fuchs theory [28]. In this theory the space surrounding a particle was divided into two regions. In the outer region ions move according to the continuum diffusion equation, whereas in the inner region they move as in a vacuum, it means that they have no collision with air molecules. By assuming this ion attachment mechanism, Hoppl et al. [24] showed that for aerosol particles smaller than 20 nm the probability that a particle acquires two or more net charges of either sign is practically zero. So there are only three different charges for aerosols below 20 nm: neutral, singly positive and singly negative. Alonso et al. [29] recalculated the ion

| Granular bed properties. |
|--------------------------|----------------|
| Granular filter parameter | Value  |
| Granular size, \( d_g \) (mm) | 2 |
| Porosity, \( \varepsilon \) | 0.375 |
| Bed thickness, \( L \) (mm) | 25, 76, 127 |
| Flow rate, \( Q \) (lpm) | 27, 45, 65 |
attachment rate coefficient of Fuchs theory [28] for the particle diameter range between 2 nm and 20 nm with using the values of ionic mass of \( m^+ = 150 \text{ amu} \) and \( m^- = 80 \text{ amu} \), and ion mobilities of \( Z^+ = 1.15 \text{ cm}^2/\text{v} \cdot \text{s} \) and \( Z^- = 1.65 \text{ cm}^2/\text{v} \cdot \text{s} \). So the probabilities (denoted as \( P \)) of the ion attachments onto the neutral, positive and negative particles are as follow:

\[
P^{+0} = 2.19 \times 10^{-9} d_p^{1.51} \tag{10}
\]
\[
P^{-0} = 3.02 \times 10^{-9} d_p^{1.51} \tag{11}
\]
\[
P^{+} = \left( 5.68 + 3.38d_p - 0.522d_p^2 + 0.042d_p^3 - 0.0017d_p^4 + 0.000027d_p^5 \right) \times 10^{-7} \tag{12}
\]
\[
P^{-} = \left( 2.15 + 4.20d_p - 0.526d_p^2 + 0.038d_p^3 - 0.0014d_p^4 + 0.000020d_p^5 \right) \times 10^{-7}. \tag{13}
\]

For example, \( P^{+0} \) shows the probability of attaching the positive ion to the neutral particle. Fig. 4 shows the probabilities of the ion collision onto the particles vs. the diameter of particles by the Alonso theory. As seen from this chart, the probability of attachment of negative ions into positive particles is greater than the probability of attachment of positive ions into negative particles. Besides, the probability of attachment of negative ions into neutral particles is greater than the probability of attachment of positive ions into neutral particles. So at the end of the neutralizing process negatively charged particles are predominant over positive ones for particle smaller than 20 nm. Since the glass beads carry negative ions, the removal efficiencies for particles smaller than 20 nm were likely reduced because the glass beads tend to repel the incoming aerosol particles.

On the other hand, Christopher et al. [30] examined the positive unipolar diffusion charging in the range of 50–200 nm. He showed that particles can get more net charges by increasing the size of them. For instance the 200 nm particle can get eleven positive ions. So the electrostatic forces cause larger particles to be removed at a high efficiency with the present of electrostatic forces.

Marlow et al. [31] demonstrated that there was a significant difference in polarity between the larger and smaller ones, when particles pass through the same bipolar charger, which is the neutralizer in this study. In the charging process of polydisperse particles, due to unequal charging rates, large and small particle may show different polarities. Since the polarity of the collector in the packed bed was certain, there must be a repulsive force for either large or small particles.

So by the above analysis we concluded that during the process of neutralizing, particles below smaller than 20 nm get different charges from the larger ones and because of this they have shown different behaviors through filtration. Small particles have the same charges as granules so the electrostatic forces might have adverse effect on filtration efficiency. On the other hand, larger particles and granules have different charges so the electrostatic forces increase the filtration efficiency.

4.2. Effect of air flow on electrostatic force

Fig. 3 does not show obvious trend for dependency of filtration efficiency based on electrostatic forces on aerosol flow rate. Fig. 3a shows that the high air flow rate (65 lpm) corresponds to the lowest efficiency by electrostatic attraction; however, Fig. 3c shows the opposite trend: the higher air flow rate corresponds to the lowest filtration efficiency by electrostatic attraction. And the difference in filtration efficiency by electrostatic attraction in Fig. 3b is negligible. Since the charges carried by the aerosol particles are assumed to be stable and consistent during the tests, these results indicate that the filtration efficiency due to electrostatic forces depends on the air flow speed and the bed thickness. To understand the mechanism behind this discrepancy, the results were presented in terms of characteristic residence time, which is defined as

\[
\tau = \frac{HA}{Q} \tag{15}
\]

where \( A \) is the cross section area of the air flow, \( H \) the bed thickness, and \( Q \) the air flow rate. Since the area of the test apparatus was the same all the time, we can use \( H/Q \) as an indicator of the residence time. The particle separation efficiencies due to electrostatic force at different \( H/Q \)
values are shown in Fig. 5 below. There is an overall trend that the effect of electrostatics increases with the residence time. This agrees with theoretical analysis in Eq. (8) above, which shows that higher air speed leads to lower residence time, and lower efficiency due to electrostatic attraction. It is physically plausible because, like what happens in a plate electrostatic precipitator, a longer resident time allows more particles to be precipitated on the collector surface.

On the other hand, the same conclusion cannot be made quantitatively. A closer examination would reveal that some curves crossed each other. Furthermore, two of these nine curves do not support the conclusion, one is for $H/Q = 4.7$ (mm·min/l) and the other $H/Q = 2.0$ (mm·min/l). It indicates that there were some measurement errors in this experimental data. Therefore, a statistical analysis was conducted to quantify the correlation between residence time indicated by $H/Q$ (except for $H/Q = 2, 4.7$ (mm·min/l)) and the particle separation efficiency at each particle size in the range of 10–100 nm.

Fig. 6 shows the correlation between particle residence time and the particle separation efficiency for particles in the range of 10–100 nm. Overall, the correlation is always positive, which quantitatively supports the conclusion above that the particle separation efficiency due to electrostatic forces increases with air flow residence time. The correlation factor is weak with an obvious fluctuation for particles between 10 nm and 20 nm. It means that the electrostatic force does not affect the particle removal efficiency in this range, and only the diffusion efficiency is dominant. Also, it is likely that other factors also affected the performance in this size range. The correlation factor is between +0.6 and +0.9 for particles in the size range of ~20–80 nm with an overall increase with the particle size. Interestingly, results showed that the correlation factor decreases from about 0.7 to 0.5 (although still positive and relatively high) as the particle size increases from 80 nm to 100 nm. Thus, the results showed that the residence time may have more effects on particles in the range of 20–80 nm rather than larger ones. These phenomena may be due to the effect of other mechanisms for particle removal efficiency such as interception which may be more dominant than electrostatic forces. More investigations are needed in order to better understand the reasons behind this phenomenon.

5. Conclusion

The following conclusions can be drawn from the study in this paper. First of all, electrostatic force plays an important role in granular filtration using glass beads for nanoaerosol particles. Experimental data show that the electrostatic force has a positive effect on the filtration efficiency of nanosized particles. The efficiency due to electrostatic

![Fig. 5. Effect of residence time on the efficiency due to electrostatic forces.](image)

![Fig. 6. Correlation between particle efficiency and residence time for particles in the range of 10–100 nm.](image)
forces increased to a level of 30% when the particle sizes increased from 20 to 100 nm. Its effect on sub-20 nm particles was negligible, because these particles carry only single ion or negative ions.

In addition, there was a positive correlation between the separation efficiency due to electrostatic forces and the residence time of the air flow. The correlation is relatively strong (between 0.6 and 0.9) for particles in the range of 20–100 nm. However, it is weak for particles smaller than 20 nm.

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