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The effect of electrostatic forces on filtration efficiency of granular filters

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ABSTRACT

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.

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

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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]:

$$\eta = 1 - \exp\left[-\frac{3}{2}\frac{(1-\varepsilon)}{\varepsilon}\eta_0\left(\frac{L}{d_g}\right)\right] \tag{1}$$

where d_g is the granule diameter, L is the filter bed thickness, ε is the filter bed porosity, and η_0 is the single collector efficiency of the granular. The filter bed porosity of the filter is defined as follows [19]:

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

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:

$$\eta_0 = 1 - (1 - \eta_D)(1 - \eta_E) \tag{3}$$

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

$$\eta_D = 2.4 A_s^{\frac{1}{3}}\left(\frac{d_p}{d_g}\right)^{-0.081} Pe^{-0.715} N_{vdw}^{0.052} \tag{4}$$

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

$$A_s = \frac{2 - 2(1-\varepsilon)^{\frac{5}{3}}}{\left[2 - 3(1-\varepsilon)^{\frac{1}{3}} + 3(1-\varepsilon)^{\frac{5}{3}} - 2(1-\varepsilon)^2\right]^{\frac{1}{3}}}. \tag{5}$$

The Peclet number is defined as

$$Pe = \frac{d_g U}{D_i} \tag{6}$$

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

$$N_{vdw} = \frac{A_H}{KT} \tag{7}$$

where A_H 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]

$$\eta_E = 1 - \exp\left[\frac{-2(1-\varepsilon)Lq_P C_c E}{\pi\mu U d_g d_P}\right] \tag{8}$$

where q_P is the particle charge, C_c 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.

$$q_P = \frac{d_P K_b T}{2eK_e}\ln\left(1 + \frac{d_P K_e c_i \pi e^2 N_i t}{2K_b T}\right) \tag{9}$$

where c_i is the mean thermal speed of ions, K_b is Boltzmann constant, K_e is Columb's constant of proportionality, e is the electrocharge, and N_i is the ion concentrations in the order of 5×10^{14} ions/m^3 [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 polydispersed 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 (NRD), 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 10^7 particles/cm^3. The sheath 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