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Experimental study of a compact electrostatically assisted air coarse filter for efficient particle removal: Synergistic particle charging and filter polarizing

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ABSTRACT

Efficient particle removal technology with minimal pressure drop is urgently needed for both air purification and energy conservation. We developed a compact electrostatically assisted air (cEAA) coarse filter, whose particle removal performance is enhanced by the synergistic effect of a corona charging field and a polarizing field. We investigated the influences of charging voltage (U), polarizing distance (d_{pl}), effect of dielectric and geometric characteristics of the filter material on fraction filtration efficiency of $PM_{0.01\sim5}$, net ozone production, pressure drop and power dissipation of the cEAA coarse filter. Our experiments were performed in a ventilation duct using ambient air particulate matter. We found an optimal U between the corona charging onset voltage and the polarizing onset voltage that enhances particle filtration efficiency with nearly no net ozone production and low energy consumption. Single pass filtration efficiency for 0.3 μm particles increased from 4% to 69% with U varying from 0 to +9 kV (d_{pl} = 3.5 cm). We found that filter material of larger relative dielectric constant or larger tortuosity yields higher filtration efficiencies. During a 458-h long-term operating period, the single pass filtration efficiency of the cEAA coarse filter did not decrease but increased slightly, and the pressure drop grew from 14.3 Pa to 31.5 Pa. We present a design strategy for a cEAA coarse filter with less than 30 Pa pressure drop at 1 m/s air velocity.

1. Introduction

In China and many other developing countries, ambient air has high levels of particulate matter (PM). PM pollution not only affects the performance and longevity of machines operating [1,2], but also is associated with mortality of human beings [3–5]. Particle filtration using high efficient particulate air (HEPA) filters or electrostatic precipitators (ESP), are widely used in ventilation systems to reduce ambient indoor particulate matter. HEPA filters are highly efficient but have a relatively large pressure drop due to high packing densities [6,7]. Due to particle loading, the pressure drop of HEPA increases over time, which causes large energy consumption [8]. ESP has a relatively small pressure drop but ESP units require large space and become inefficient once dust has accumulated [9–11]. Furthermore, ESP units with short collecting plates do not efficiently capture ultrafine particles [12]. Thus, both HEPA filters and ESP have limitations which limit their lifespan in buildings' air filtration systems. The combination of electrostatic effect and fabric filtration has been proposed as a promising way to improve the particle filtration efficiency of low efficiency filters without increasing their pressure drop [13–16].

There are two ways to combine the electrostatic effect with fabric filtration: initially charging the filter fibers with an electret [1,17–19], and continuously charging externally during operation [14–16]. For initially charged electret filters, the electric charges on electrets dissipate over time so that their efficiency decreases sharply during the operating time [1,20]. For continuously charged filters, installing ionizers in front of a fibrous filter has been found to enhance the filtration efficiency of a filter without increasing the pressure drop. However, the filtration efficiency enhancement is below 8% for particles larger than 0.1 μm [13], and below 10% for particles smaller than 1 μm [16]. In these ionizer studies, only particles were charged, so the filtration efficiency enhancement was limited [15].

In addition to only charging the particles, using an external electric field to charge the filter medium promises to enhance the filtration efficiency. Feng et al. [15] developed a pin-filter medium-plate device to enhance the filter medium's filtration efficiency. The filtration efficiency for particles of 0.4 μm is as high as 97% with applied voltage of 25 kV and a pin-filter distance of 100 cm at a face air velocity of 0.1 m/

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s. However, such a low face air velocity is not practical for a ventilation system. And since both particles and filter medium were charged in the electric field between high voltage pins and grounded plate, it was difficult to optimize the filtration efficiency by adjusting particle charging and filter medium charging separately. Lee et al. [21] separated the charging fields for particles and filter medium. They used a two-stage electrostatically augmented air (EAA) filter to remove Arizona road dust and tobacco smoke. The single pass filtration efficiency for particles of 1.96 μm in mass median diameter rose from 70.0% (conventional filter without high voltage charging) to 92.9% with the two-stage charging. However, the pressure drop of the EAA filter was around 156.9 Pa, relatively high for a ventilation system.

For the present study, we developed a compact electrostatically assisted air (cEAA) coarse filter with high particle filtration efficiency enhancement and a small pressure drop. This device differs from Lee's [21] two-stage EAA filter in that only one electrode is connected to high voltage supply. We also changed the structure of two grounded electrodes to ensure that most of particles would deposit on the filter fibers instead of the grounded plates. We used unfolded coarse filters with extremely low initial efficiency (less than 10% for 0.3 μm particles) rather than medium efficiency filters to ensure a small pressure drop for the device. Our modifications, reduced the required space for the device. The purpose of this study was to experimentally evaluate these influencing factors on the performance of cEAA coarse filters: charging voltage (U), polarizing distance (d_{pl}), dielectric and geometric characteristics of the filter material. Based on experimental results, we studied the synergistic effect of particle charging and filter polarizing on filtration efficiency enhancement. We used scanning electron microscope (SEM) photographs to observe the fiber's geometric characteristics and particle depositing differences between cEAA coarse filters with different filter materials installed.

2. Methodology

2.1. cEAA coarse filter module

The configuration of the small-scale cEAA coarse filter module used in this study is shown in Fig. 1. The module's envelope is polymethyl methacrylate (PMMA). The ambient air is driven through the module in this sequence: through a front metal screen (field electrode), corona charging wires (charging electrode), a fabric filter, and a back metal screen (field electrode). There are two zones in the cEAA coarse filter module along the air flow pathway. The first consists of the charging wires and the front metal screen, and is the charging zone. The strong electric field intensity near the charging wires causes a coronal discharge, which is commonly used to produce large quantities of ions [10]. When particles flow through the charging zone, they collide with and attach to the ions, thereby acquiring charges [22,23]. The second zone consists of the charging wires and the back metal screen and is the polarizing zone. The electric field in the polarizing zone builds up through the dielectric fabric filter and polarizes it, such that the fibers have untransferable charges on their surface [24,25]. Thus, the charged particles are easily captured by polarized fibers owing to columbic force or image force [26].

The charging electrode in the cEAA module consists of an array of molybdenum wires of radius 0.01 cm and length 18 cm. The distance between each wire is 2.7 cm and between the charging wire and the parallel envelope is 2.9 cm. The distance between the charging wires and the front metal screen (charging distance, d_c) is 1.1 cm, and the distance between the charging wires and the back metal screen (polarizing distance, d_{pl}) is adjustable from 3.5 cm to 4.5 cm. The front metal screen is made of a stainless steel plate that has evenly distributed circular holes (1.5 cm in diameter) as shown in Fig. 1 (b). The back metal screen is made of iron wires as shown in Fig. 1 (c). The charging wires are connected to a 0 ∼ +10 kV adjustable high voltage direct current (HVDC) power supply (P10, GENVOLT, China). We use positive rather than negative discharging because of its lower ozone production in the DC corona [27–29]. The front and back screens are both connected to ground.

2.2. Theoretical analysis for cEAA coarse filters

For a charged particle and neutral dielectric cylindrical fiber in an external electric field, the radial electrical force F_r is [30]:

$$F_r = E_e q_p \left[1 + \left(\frac{\varepsilon_r - 1}{\varepsilon_r + 1}\right)\frac{D_f^2}{4R^2}\right] \tag{1}$$

where E_e is the external electric field intensity, assumed to be perpendicular to the center line of the fiber and to pass through the center of the particle; q_p is the particle's charge; ε_r is the relative dielectric constant of the fiber; D_f is the fiber diameter; and R is the distance between the centerline of the cylindrical fiber and the center of the particle. The larger the radial electrical force, the higher the filtration efficiency.

In previous research, the radial electrical force was enhanced by increasing q_p, and q_p was increased by applying stronger charging field intensity, or by using abundant ionizers [13,31,32]. Increasing charging field intensity generally leads to an increase in loop current. Equation (1) shows that increasing the polarizing field intensity (E_e) can also enhance the radial electrical force but without increasing loop current. When the loop current of the device grows, the energy consumption and the ozone production increase. In our cEAA coarse filter, the corona charging field intensity and the polarizing field intensity share the same U (Fig. 1). Therefore, optimizing the synergy between the corona charging field intensity and the polarizing field intensity is critical for both maximizing the single-pass filtration efficiency and minimizing ozone production.

For coronal discharging, Davies et al. [33,34] studied the corona onset voltage between a positive charging wire and a grounded plate. The structure of a cEAA filter (Fig. 1) is such that the grounded screens are not plates but have holes in them. Since the corona conducts only around the wire, we consider the wire-screen structure as a wire-plate structure. The corona onset voltage (V_{ons}) was calculated as [35,36]:

$$V_{ons} = E_{ons}\frac{r\cdot\ln\left(\frac{d_c + r}{r}\right)}{0.9} \tag{2}$$

$$E_{ons} = E_0\delta\left(1 + \frac{h - 1}{100}\right)\cdot\left(1 + \frac{0.308}{\sqrt{\delta\, r}}\right) \tag{3}$$

$$\delta = \frac{273 + T_0}{273 + T}\cdot\frac{p}{p_0} \tag{4}$$

where V_{ons} (kV) is the corona onset voltage between the charging wires and the front screen; r (cm) is the radius of the charging wire; d_c (cm) is the distance between the charging wires and the front screen; E_{ons} (kV/cm) is the corona onset field intensity, and E_0 is the standard onset field intensity, 31 kV/cm [33]; δ is the relative air density, which is a function of ambient air centigrade temperature (T) and atmosphere pressure (p); h (g/m^3) is the humidity ratio of ambient air; T_0 and p_0 are the standard temperature (25 °C) and standard atmospheric pressure (101.325 kPa), respectively.

Since the charging distance d_c is shorter than the polarizing distance d_{pl}, the corona onset can only occur in the charging zone. However, d_{pl} may influence the corona charging field intensity, and therefore influence the charging process of a cEAA coarse filter device. Thus, we supposed that there is a corona onset voltage for the polarizing zone, and described the influence of d_{pl} on the charging process by using $V_{ons,p}$, which was calculated as:

$$V_{ons,p} = E_{ons}\frac{r\cdot\ln\left(\frac{d_{pl} + r}{r}\right)}{0.9} \tag{5}$$