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Novel electrodes of an electrostatic precipitator for air filtration

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ABSTRACT

Using electrostatic precipitators (ESPs) in filtration systems results in higher system energy efficiency than fiber-based filters, but particle re-entrainment could lower the collection efficiency of ESPs. This paper demonstrates a novel ESP that utilizes foam-covered collecting electrodes to reduce particle re-entrainment and enhance collection efficiency. Particles that settle down within the pores of the foam are less likely to re-enter the airflow. Results show that foam-covered ESPs have 99 percent collection efficiency. Parametric plots demonstrate the effects of the key design variables, such as corona voltage, repelling voltage, and free airflow velocity on collection efficiency.

Introduction

While the principles of ionic wind purification have been known for decades, its commercial use has been mostly limited to industrial electrostatic precipitators (ESPs), which operate in temperatures that are too high for fiber-based filters. For instance, ESPs are normally used to clean the exhaust from coal plants [1,2], metallurgical plants, and chemical factories [3]. The total mass collection efficiency of an ESP is high; however, this can be misleading when coming to HVAC applications (heating, ventilation, and air conditioning) in residential and commercial buildings. One coarse particle may weigh as much as 100,000 fine particles, whereas fine particles are the primary concern for respiratory health. Many commercial filters have an ESP stage, augmented by a pre-filter and/or a post-filter, exactly for the reasons that the ESP stage does not remove particles across the desired range with a sufficient efficiency. This paper attempts to develop new ESPs that have high particle removal rates for submicron particles while maintaining a low pressure drop, in order to bring ESPs one step closer toward non-industrial applications.

The main components of a filtration system are the fans and the filters. Fans are used to bring air into or out of the system, whereas filters are used to remove aerosol particles out of the air stream. Using ESPs in filtration systems is more energy efficient than using fiber-based filters, because ESPs have less resistance to the airflow. Fiber-based filters function by placing a dense mesh of fibers into the path of airflow. Unwanted aerosol particles attach to the surfaces of the fiber, which results in clean air at the outlet. However, pushing air through a meshed fiber requires significant pressure, which is provided by powerful energy-consuming fans. Moreover, as the filtration media accumulates dust in its structures, the required pressure increases several fold; thus, frequent maintenance is required to minimize energy use. In contrast, ESPs use plate electrodes located along the airflow path. These electrodes do not obstruct the airflow too much. In fact, the device can generate "negative" back pressure, since the ionized air is actually pulled through the device by electrostatic force. Additionally, ESPs do not significantly lose collection efficiency when dust accumulates on the surface of the plate electrodes. Thus, it is believed that ESPs are fundamentally more energy efficient than fiber-based filters.

A schematic of a traditional two-stage ESP is shown in Fig. 1. A fan (not shown) draws air and particles into the system. Suspended particles are charged by the acquisition of ions and/or electrons that are generated through the corona discharging processes in the charger [4]. As the charged particles pass through the collector, the strong electric force causes the charged particles to change their moving trajectories and settle down onto the collecting electrodes.

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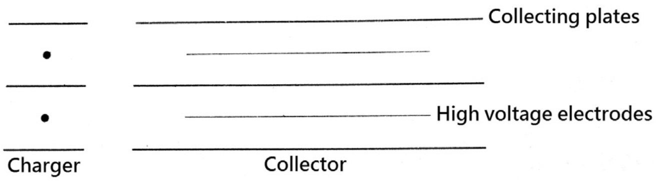

Fig. 1. A schematic of the traditional two-stage ESP [5].

As a result, the particles in the air stream are removed. For some commercially available ESPs, fibrous filters are placed before charger and/or after collector to capture the particles that are not able to be captured by the electrostatic stage.

The following technological developments have made ESPs more competitive. First, new collecting and repelling electrode geometries have dramatically increased the resulting collection efficiency [6–11]. The performance of ESPs with new electrode geometries matches or even exceeds most fiber-based filters at the same air flow rates. The new electrode geometries simultaneously lower filter back pressure, allowing for significant reductions in the size and the power of the fans, which results in substantial energy savings [12,13]. Second, high-voltage electronics with microprocessor control allow for operation at high collection efficiencies, despite environmental changes. Third, ozone generation can be reduced to background levels due to proper material selection of the corona electrodes [14–16].

Nonetheless, the settled particles still have a chance of returning to the environment for many reasons, such as vibrations or passing airflow [4,17–19], which lowers the collection efficiency. In order to minimize the effects of particle re-entrainment and to remove the need for pre- and/or post-filters while maintaining high ratings of collection efficiency, this paper presents a novel particle-trapping mechanism added onto the collecting electrodes in an ESP. By covering the collecting electrodes with a porous material that has low electrical conductivity, the drawbacks of traditional ESPs can be overcome [20]. First, the porous structure of the foam allows the particles to penetrate deep into the pores, leaving the surface of the collecting electrodes nearly clean for a long duration, and sharply eliminates the chance of particles re-entering the environment. Second, the low electrical conductivity of the foam prevents spark discharge between the electrodes. When spark discharge (short circuit) occurs between the electrodes, there is no electric field between the electrodes, which means the ESP is not working properly at that moment. Third, the low electrical conductivity of the foam also keeps the conductive dust from fast discharging. Additionally, the foam is flame-retardant, so there is little risk of causing a fire.

This paper presents the working principles of ESPs and provides a comprehensive discussion on the design concepts and schematics of a foam-covered ESP. Experimental results show that the collection efficiency of foam-covered ESPs is competitive to that of fiber-based filters, allowing ESPs to be used for commercial or residential applications. Additionally, this paper examines the collection efficiency of foam-covered ESPs by looking at the effects and interactions of the corona voltages and repelling voltages, as well as the free airflow velocities.

Technical background

ESPs are electrohydrodynamic (EHD)-based systems that have the coupling behavior of electrostatic interactions and fluid motions. The governing equations for these two physics are the Poisson's equation, the charge transport equation, the Navier–Stokes equation, and the continuity equation [21–23].

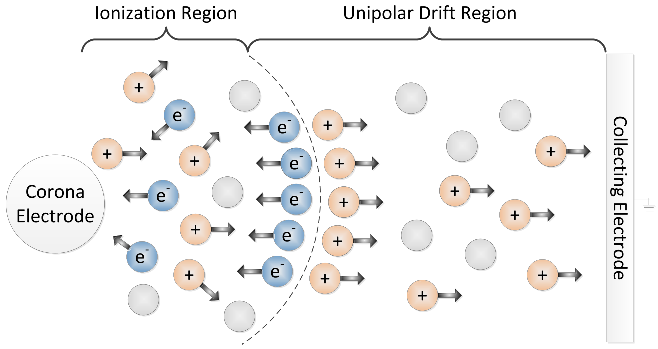

Fig. 2. A model of positive discharge. There are two regions between the corona and collecting electrodes. The ionization region, or corona plasma region, surrounds the corona electrode. The unipolar drift region is the region between the ionization boundary and the collecting electrode.

For a positive discharge model, as shown in Fig. 2, the corona electrode operates at a high positive voltage, and the collecting electrode is usually grounded. Hence, there is a high intensity electric field between the corona and collecting electrodes. Particles are positively charged by gaining additional positive ions emitted from the corona discharging process at the corona electrode. Positively charged particles are repelled against the corona electrode, and then travel toward the collecting electrode in accordance with the electric field, and finally, settle down on the collecting electrode.

There are two regions between the corona and collecting electrodes. The first region is the ionization region, which exists very close to the corona electrode. There are both positive and negative ions inside this region. Because the radius of the corona electrode is much smaller than the radius of the collecting electrode and the distance between the corona and collecting electrodes, the characteristics of the ionization region can be evaluated by Peek's law [24] and Kaptsov's assumption [25–27]. Peek's law can be used to estimate the electric field at the corona electrode surface, while Kaptsov's assumption states that when corona discharge occurs, the electric field strength at the ionization boundary equals the breakdown electric field strength of the fluid, which, in this case, is air. The second region is the unipolar drift region, where the charged particles travel toward the collecting electrode. During the movement of those charged particles, they collide with other neutral particles, which transfer charges and momentum to them. As a result, more charged particles can be captured by the collecting electrode. Within this region, the moving particles obey classic fluid dynamics, which is represented by the Navier–Stokes equations.

Experimental setup and prototype design

Experimental setup

Fig. 3 shows the experimental setup. Air is drawn into the system using traditional fans, and then flows through a flow straightener to ensure uniform airflow. The airflow velocity, from 0.5 m/s to 2.5 m/s, is varied through adjustments to the input power of the fans. The air then flows through the foam-covered ESP prototype. The particle counter (Haltech HPC600) is placed right after the ESP to measure the number of particles in the air stream, in terms of particle sizes. The minimum measurable particle size is 0.3 μm, and the particle counting efficiency is 100 ± 10% at 0.45 μm. A voltage DC power supply (Hipotronics) provides positive high voltage to the corona electrodes, and another power supply