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The key energy performance of novel electrostatic precipitators

Tsrong-Yi Wen [a], Igor Krichtafovitch [b], Alexander V. Mamishev [a,c,*]

[a] *Department of Mechanical Engineering, University of Washington, Seattle, WA, United States*
[b] *Pacific Air Filtration, Inc., Seattle, WA, United States*
[c] *Department of Electrical Engineering, University of Washington, 185 Stevans Way, Box 352500, Seattle, WA 98195, United States*

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ABSTRACT

Energy consumption of a filtration system depends largely on the pressure drop across the air ducts. The magnitude of this pressure drop is largely dependent on the presence of air filters designed to remove particles from the air stream. However, evaluating the performance of air filters by looking only at their pressure drop or collection efficiency is misleading because these two factors are not linearly dependent. A more rigorous approach uses key energy performance (KEP) to assess air filter performance, because KEP involves both collection efficiency and pressure drop. This paper provides methodology for the evaluation of performance of different types of filters, comparing the KEP of one fiber-based filter and three electrostatic precipitators (ESPs). One of the ESPs is commercially available, while the other two have novel particle-trapping mechanisms developed by our research group that substantially increase collection efficiency. The results show that, although all electrostatic precipitators have KEPs of at least nine times higher than fiber-based filters, newly developed electrostatic precipitators have KEPs of nearly twice as high as their commercially available counterparts. This paper also examines how three different operating conditions affect the KEPs of ESPs, and presents an example of energy savings in a filtration system when fiber-based filters are replaced with electrostatic precipitators.

1. Introduction

Air filtration systems are used universally in commercial, industrial, medical, and manufacturing facilities. Energy consumed by these systems depends mostly on the length of air ducts, density of mesh filters inserted in the airflow, and speed of operation of fans used to propel air through the ducts. The denser the filter mesh, the greater the pressure drop across the filter. In order to overcome a higher pressure drop, fans need to operate at higher speeds, therefore consuming larger amounts of energy. Thus, one of the main elements of an air filtration system is finding an engineering trade-off, where the filter mesh is dense enough to capture the required percentage of particles in the air and yet not so dense as to become economically prohibitive.

Evaluating the performance of an air filter by looking only at the filter's collection efficiency or pressure drop is misleading. The collection efficiency is not always in a linear relationship with the pressure drop, especially in the case of non-industrial applications. The key energy performance (KEP) involves both collection efficiency and pressure drop, and is a more impartial method of evaluating air filters. Lowering pressure drop and increasing collection efficiency is crucial to improving the KEPs of air filters. This paper analyzes and compares the KEPs of fiber-based filters and electrostatic precipitators (ESPs).

The particle-removing mechanism of fiber-based filters is a passive process in which particles in the air stream are removed when they attach to the fibers. The presence of the mesh in the path of the airflow results in a large pressure drop. In contrast, electrostatic precipitators have significantly lower pressure drop than fiber-based filters, because the plate electrodes of electrostatic precipitators are arranged along the direction of the airflow. In two-stage ESPs, the subject of this study, the particles are charged by gaining additional ions generated from the ionization processes near the corona electrode. The charged particles move along the electric field that exists between the repelling and collecting electrodes, and settle on the collecting electrodes. In summary, fewer obstacles obstruct the airflow in electrostatic precipitators than in fiber-based filters, which, in principle, allows for a more energy-efficient operation.

However, state-of-the-art ESPs, generally speaking, are less efficient in removing particles from the air stream than their mesh-based counterparts. 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 of particle sizes. Nevertheless, the implementation

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[*] Corresponding author at: Department of Electrical Engineering, University of Washington, Box 352500, Seattle, WA 98195, United States. Fax: +1 206 543 3842.
E-mail address: mamishev@ee.washington.edu (A.V. Mamishev).

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of pre- and/or post-filters impedes airflow and increases the pressure drop of the system. Our research group previously presented two novel particle-trapping mechanisms that promoted the collection efficiencies of ESPs despite the absence of fibrous filters [1–3]. For a foam-covered ESP (FC-ESP), the collecting electrode is covered by porous foam. Particles attach to the surface inside the pores of the foam instead of the flat surface of the bare collecting electrode. For a guidance-plate-covered ESP (GPC-ESP), the collecting electrode is covered by a guidance plate that has patterned holes on it. Gaps are intentionally left between the guidance plate and the collecting electrode to allow particles to enter through the holes and stay inside the gaps. The particles collected by such particle-trapping mechanisms have a lower chance of returning to the air stream because there are fewer disturbances inside the pores or gaps than there are on the flat surfaces of the bare collecting electrodes. FC-ESPs are able to collect ultra-fine particles and lower the chance of sparkover between the electrodes. GPC-ESPs, on the other hand, have non-consumable parts on the collecting electrodes and are able to accommodate larger amounts of particles.

At the beginning of this paper, an introduction to fiber-based filters and electrostatic precipitators, including two newly developed ESPs with particle-trapping mechanisms, is presented. After that, this paper compares the KEPs of fiber-based filters and foam-covered electrostatic precipitators. A parametric study on how operating conditions affect the KEPs of guidance-plate-covered ESPs is then brought out. At the end of this paper, a real-life example of how replacing fiber-based filters with electrostatic precipitators in a filtration system affects energy costs is demonstrated.

2. Background of air filters

2.1. Fiber-based filter

Fiber-based filters are usually made out of a dense mesh of fiberglass. Particles are unable to pass through fiberglass mesh because of three capturing mechanisms: impaction, interception, and diffusion [4], as illustrated in Fig. 1. The impaction mechanism implies that large particles directly impact the mesh structures and are captured. The interception mechanism implies that large particles cannot pass through the pores of the mesh structures consequently stick to the pores or the mesh structures instead. The diffusion mechanism refers to the Brownian motion, which states that the interactive motions of moving particles and air molecules affect the moving trajectories of ultra-small particles (smaller than 0.1 μm). In other words, such ultra-small particles are captured by chance because the interactive motions between the particles and air molecules increase the probability for the particles to be captured by the mesh structures of the filters. In addition to the capturing mechanisms mentioned above, electrets are often used to enhance filter's collection efficiency. An amount of charges is implanted in the electret fibers, such that there are electric fields between the electret fibers. Certain particles could be collected by the electret fibers because of the induced electrostatic forces.

The collection efficiency of fiber-based filters depends on several parameters, such as the diameter of the fiber, the material of the fiber, the density of the mesh, and the thickness of the filter. Other external factors, such as the properties of the particles and the density of accumulated particles on the fibers, also have a considerable influence on the collection efficiency of fiber-based filters.

The American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) rates the performance of fiber-based filters in terms of the minimum efficiency reporting value (MERV). The MERV has 16 official ratings (1–16) and four comparative ratings (17–20) [5]. Each rating has different collection efficiencies for three ranges of particle sizes. For residential applications, ASHRAE suggests a filter with a minimum rating of MERV 6 [6]. The American Society of Mechanical Engineers (ASME) requires a high-efficiency particulate air (HEPA) filter to be capable of removing at least 99.97% of dioctyl phthalate particles larger than 0.3 μm in diameter [7]. According to the MERV ratings, a MERV 17 filter is equivalent to a HEPA filter.

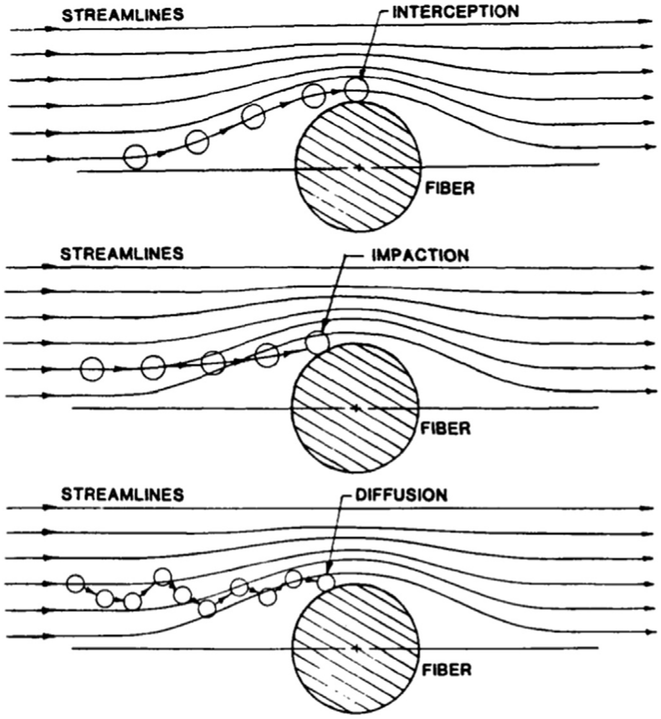

Fig. 1. Capture mechanisms of fiber-based filters: impaction, interception, and diffusion [4].

Fiber-based filters are the most widely used filters because of their simple structures, easy installations, and low costs. However, fiber-based filters are not ideal for high temperature applications, such as coal plants [8,9], metallurgical plants, and chemical factories [10], where high temperatures may lead to fire hazards. Fiber-based filters are also unsuitable for highly dusty environments, as these conditions result in frequent maintenances or replacements. One of the most significant concerns of using fiber-based filters in a filtration system is that the fans consume large amounts of energy in order to overcome the high pressure drop across the filters. In addition, the pressure drop across fiber-based filters increases over time because of particle accumulation, causing the energy supplied to the fans to increase accordingly, sometimes several fold, to maintain a specific airflow rate.

2.2. Electrostatic precipitators

Electrostatic precipitators are electrohydrodynamics-based air cleaners that utilize corona discharge and the electric field as their driving forces. The underlying principles behind electrohydrodynamics are fluid dynamics, electrostatics, and charge transport [11]. Fig. 2 shows a model of positive discharge. The corona electrode operates at a high positive voltage while the collecting electrode is grounded, creating between them an ionization region and a unipolar region. The ionization region is near the corona electrode. In this region, the electric field intensity is extremely high because there is a huge curvature difference between the corona and collecting electrodes. Once free electrons