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Numerical study of electrostatic precipitators with novel particle-trapping mechanism

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ABSTRACT

Guidance-plate-covered electrostatic precipitators (GPC-ESPs), which are ESPs with perforated guidance plates that cover their collecting electrodes, have been experimentally proven to have higher collection efficiencies than their traditional counterparts. The key to the GPC-ESP's success in high collection efficiency is that particles that enter the gaps between the guidance plate and the collecting electrode have lower chances of returning to the environment. This paper presents the characteristics of the GPC-ESPs, and discusses how the parameters of interest affect collection efficiency. The numerical model is carried out by modeling the particle transport, flow field, and electric field. Results show that when the diameters of the holes on the guidance plate are larger, the flow recirculation is stronger and allows for more particles to easily enter the gaps through these holes. The electrical characteristics are dependent on the repelling voltage and the diameter of the holes. The collection efficiency is also discussed in terms of two dimensionless parameters: the Stokes numbers (the ratio of inertia force to viscous drag force) and the electrostatic numbers (the ratio of electrostatic force to viscous drag force). Results show that a lower Stokes number and a higher electrostatic number results in a higher collection efficiency. The collection efficiency remains numerically unchanged when the electrostatic number stays the same. This paper also demonstrates a set of simulations to simulate particle re-entrainment. Results show that when particle re-entrainment happens at the collecting electrode, none of the particles reenter the environment through the holes of the guidance plate. When particle re-entrainment happens at the guidance plate, some of the particles escape the collector, but most of the particles enter the gaps and are recaptured at the collecting electrode, due to either flow recirculation or induced electrostatic forces.

1. Introduction

Particle-induced air pollution receives considerable attention, because fine particles cause serious health problems, such as ischemic stroke, respiratory disease, and cardiovascular disease (Brook et al., 2010; Dockery & Pope, 1994; Pope & Dockery (2006); Wellenius et al., 2012). Electrostatic precipitators (ESPs) are commonly used to collect particles from the air.

A traditional two-stage ESP consists of a charger (in the upstream) and a collector (in the downstream). When particles enter the system, they are charged in the charger, and then move toward the collector. The collector has a strong electric field between the repelling electrodes (high voltage) and collecting electrodes (usually grounded), so that charged particles are subjected to electric forces and travel to the collecting electrodes, where they settle.

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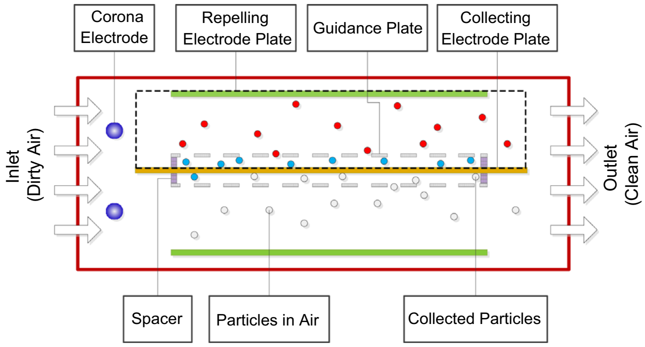

Fig. 1. A schematic of a GPC-ESP. The black dashed rectangle is the simulation domain. Not drawn to scale.

The collection efficiency of ESPs is a function of numerous parameters, including particle size, electrodes' geometry, applied voltage, and airflow velocity (Mizuno, 2000; Oglesby & Nichols, 1978). The collection efficiency of an ESP is also affected by abnormal power outages and disturbances, such as air turbulence and vibrations (Ferge, Maguhn, Felber & Zimmermann, 2004; Tsai & Mills, 1995; Zukeran et al., 1999). In other words, the collected particles have a chance of being dislodged from the collecting electrode, thus reentering the air stream (known as particle re-entrainment). For non-industrial applications, many commercial ESPs use a fiber-based filter placed right after the ESP stage to capture particles that are dislodged from, or are not captured during the ESP stage. However, introduction of a fiber-based filter increases the pressure drop and energy usage (Wen, Krichtafovitch & Mamishev, 2015b), making these types of ESPs less economically efficient.

There are four methods to reduce particle re-entrainment. The first method is to enhance the adhesion between particles and collecting electrodes by introducing water films or wet membranes on (or in place of) the collecting electrodes (Bayless, Alam, Radcliff & Caine, 2004; Bologa, Paur, Seifert, Wascher & Woletz, 2009; Jaworek, Balachandran, Krupa, Kulon & Lackowski, 2006; Triscori, Moretti, Snyder & Tonn, 2009; Tsai & Lin, 2012). The second method is to collect particles in a designed pocket zone (on the collecting electrode) that has no electric field (Yamamoto et al., 2009). The third method consists of covering the collecting electrode with porous foam. Particles that are collected in the pores of the foam have a lower chance of returning to the air stream, because disturbances inside the pores are far weaker than they are on the flat and bare collecting electrodes (Krichtafovitch, Wen & Mamishev, 2013; Wen, Wang, Krichtafovitch & Mamishev, 2015). Similar to the third mechanism that traps particles in a weaker disturbance space, the fourth method, which this paper focuses on, is to cover the collecting electrodes with perforated guidance plates. Figure. 1 shows the schematic of a guidance-plate-covered ESP (GPC-ESP). Particles can go through the holes of the guidance plates and stay in gaps between the guidance plate and the collecting electrode. Because disturbances in gaps are relatively weaker than in the bare and flat collecting electrodes, particles collected in these gaps have a lower chance of returning to the environment. This scheme has been experimentally proven to have higher collection efficiencies than its traditional counterpart (Wen, Krichtafovitch & Mamishev, 2015a) without introducing any fiber-based filters, making GPC-ESPs very economically efficient (Wen et al., 2015b).

This paper employs a numerical model to depict the characteristics of GPC-ESPs to provide a reference for future optimized design. The beginning of this paper discusses the theory behind the numerical model. This is followed by discussions on the characteristics of the flow fields, voltage fields, electrostatic fields, particle trajectories, and collection efficiencies. Additionally, this paper also presents a simplified model to simulate particle re-entrainment. A full discussion on simulated particle re-entrainment provides evidence that covering the collecting electrode with the guidance plate does minimize the chances of particle re-entrainment.

2. Theory

2.1. Electric and flow fields

It is assumed that the particle concentration is low enough and does not alter the space charge density. The electric field is solved by using Poisson's equation. The standard linear k-ε RANS model is used to predict the velocity field, because only the mean velocity field is needed in deriving the particle trajectory (Suh & Kim, 1996).

2.2. Particle charging

The pioneer researchers have showed that the total particle charges are sufficiently reliable by adding up the field charging rate and the diffusion charging rate (Hewitt, 1957; Kim & Lee, 1999; Smith & McDonald, 1975, 1976; Vincent & MacLennan, 1980). Particles that are larger than 0.5 μm are charged by gaining additional ions from the collisions with other