Electrostatic Precipitator Efficiency: A Study of Wire Layout

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***Abstract*—In this paper, we use an electrostatics approach to model a basic electrostatic precipitator, a type of device that is used to to filter harmful particles from air in industrial applications. We analyze the relative efficiency of various wire layouts by comparing the ratio of collected particles to the amount of particles that enter the device and conclude that operational efficiency has a greater dependence on electrode spacing than on amount of electrodes in the system.**

I. Introduction

Electrostatic precipitation is a form of air filtration commonly used in industrial settings. The precipitation process utilizes the force of an applied electrostatic charge to efficiently collect dirty or harmful particles while maintaining air circulation [2]. Electrostatic precipitators typically collect particulate matter of 10-20 μm in size. They are capable of filtering both solid and liquid particle emissions from machinery such as furnaces, boilers, and smelters [5]. Particles passing through an electrostatic precipitator undergo two stages of filtration: ionization and collection (see figure 1).

Initially, the flow of air transports uncharged particles near discharge electrodes with a high negative charge (40 - 50 kV). In an electrostatic precipitator, the strength of the electric field produced by discharge electrodes exceeds the dielectric strength of air ($3 \times 10^6 V/m$), causing the surrounding air to break down and partially ionize, forming a corona [3] of ions. When uncharged particles enter this "breakdown region" [1], they collide with these ions and gain a negative charge. Once the particles are charged, they travel along the electric field lines toward positively charged collection electrodes. A common electrostatic precipitator design uses positively charged parallel plate conductors as collection electrodes. The negatively charged particles remain on the plates until they are removed through mechanical

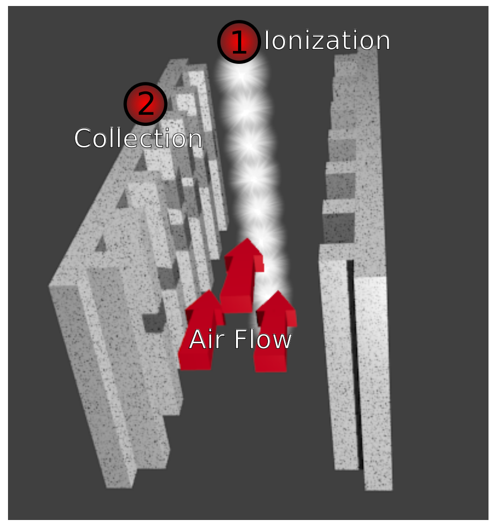

Fig. 1. A simplified representation of the two main stages of an electrostatic precipitator.

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Manuscript submitted February 3, 2011; revised February 10, 2011.

processes. Electrostatic precipitators generally contain rappers, physical devices that can employ pneumatic or magnetic means to dislodge the particles stuck to the plates. The particles then fall into a hopper, where they are stored for later disposal. [4]. In this paper, we explore the efficiency of the initial collection process by developing a simple model to understand the effect of varying the discharge electrode configuration. In the next section, we explain the model used to simulate the precipitation process.

II. The Model

To simplify the process of modeling particle flow, we represent a basic electrostatic precipitator as two positively charged vertical plates surrounding a configuration of negatively charged wires. Because we are concerned solely with the role of the discharge electrode configuration, we focus on the ionization and collection processes, and disregard the roles of the rapper and hopper in the removal of particles once they have been collected.

A. The Electric Field

We model dirty particulates as point charges using the principles of electrostatics and superposition to calculate the electric field acting on a single particle at a time; for the sake of simplicity, we make the assumption that charged dust particles exert no force on one another. We also consider that (1) the discharge and collection electrodes can be approximated using evenly-spaced point charges, (2) the collection plates and discharge wires have a uniform charge distribution, and (3) there is no net charge in the system.

We use Coulombs Law,

$$\vec{E}(\vec{r}) = \frac{\sigma}{4\pi\epsilon_0} \int_S \frac{\vec{r} - \vec{r'}}{|\vec{r} - \vec{r'}|^3} \qquad (1)$$

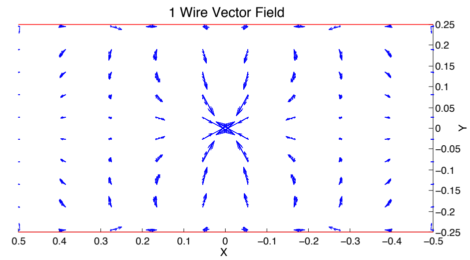

Fig. 2. A vector plot depicting the flow of charge from two positive plates to a single negative wire located at the center of the image. Note that we used SI units; the dimensions of the plates are in meters. The charge distribution is $2.5 \times 10^{(} - 5)$ per plate. Since the total charge in the system is 0, the wire in this example has a charge distribution of $-5 \times 10^{(} - 5)$

to compute the electric field $\vec{E}$ at a point $\vec{r}$ occupied by a particle at discrete time steps. Here ϵ_0 represents the permittivity of free space, σ is the charge distribution, and $\vec{r'}$ corresponds to the location of a source charge on the surface S over which the integration takes place. Qualitatively, the electric field points away from the positively charged plates and toward the negatively charged wires. This behavior is demonstrated in figure 2. The electric field is strongest near the plates and wires.

1) Validating the Electric Field: To validate the electrical field produced by the charged plates and wires, we calculate the potential

$$V(\vec{r}) = \frac{1}{4\pi\epsilon_0} \int \frac{dQ}{|\vec{r}|} \qquad (2)$$

where $V(\vec{r})$ corresponds to the potential at a point $\vec{r}$, ϵ_0 represents the permittivity of free space, and dQ is the charge distribution. Figure 3 displays a potential plot of the electrostatic precipitator for a single centered wire.

B. Corona and Particle Charging

Uncharged particles entering an electrostatic precipitator are ionized when they enter the breakdown region that surrounds the negatively charged wire electrodes. Our simulation compares the strength of the electric field

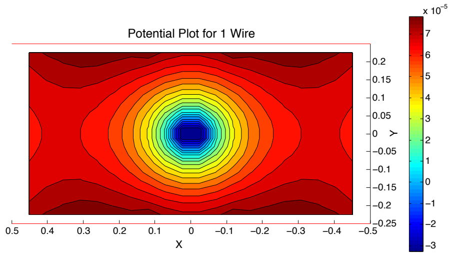

Fig. 3. This diagram presents a visualization of the electric field plot shown in figure 2 converted to potential (also known as voltage). The black curves represent equipotential lines, while various colors correspond to the magnitude of the equipotentials. This figure demonstrates the side-effects of using an electrostatics approach for simulation - the top and bottom equipotential lines would be straight in a more accurate simulation.

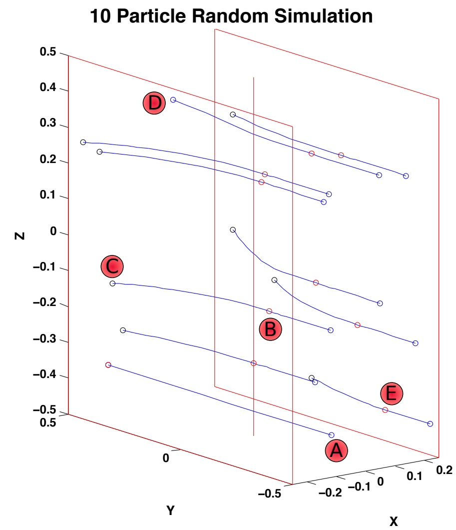

Fig. 4. A simulation of ten particles with random bounded starting positions on the x,z plane. Uncharged dust particles are represented by blue circles (A) and follow blue trajectories until they become charged (B) and are collected (C) or escape the electrostatic precipitator (D). Some particles (E) become charged before they enter the breakdown field produced by the wires or become charged just before they leave the plates. A limitation of the simulation process is that only the magnitude of the field at a point is taken into account when a particle is charged and that fringe effects occur near the plate boundaries.

to the dielectric strength of air as a test to determine if a particle is within the corona. Given the high density of ions in the corona, we assume that any uncharged particle that enters this region instantaneously acquires one electron worth of charge.

C. Particle Migration and Collection

We can use the Lorentz Force Law,

$$\vec{F} = (q)(\vec{E}) \tag{3}$$

to simulate the motion of a charged particle. $\vec{F}$ is the electric force in Newtons, q is the electric charge of the particle in Coulombs, and $\vec{E}$ represents the electric field Volts/m. From this equation, we see that the force on a negatively charged particle acts in the direction opposite to that of the electric field. For the simulation, we assume that the force of drag acting on the particles is negligible. If this is the case, we realize that the particle's acceleration is only dependent on the force of the electric field. The acceleration of the particle can be calculated using Newtons Second Law of Motion,

$$\ddot{\vec{r}} = \frac{\vec{F}}{m} \tag{4}$$

where F is the force in Newtons, m is the mass of the particle in kilograms, and $\ddot{\vec{r}}$ is the acceleration in $\frac{m}{s^2}$. For the simulation, we assign each particle a uniform mass, assuming a constant particle size. We use an ordinary differential equation (ODE) solver to simulate the movement of the particle.

We simulate the collection of charged particles by the collector plates by stopping the simulation of a particle once its distance to one of the plates becomes small. These stages of simulation are depicted in figure 4 for ten particles affected by a single discharge wire in the xz plane.

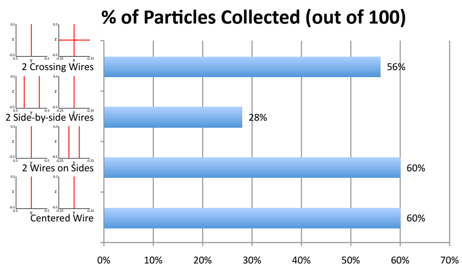

Fig. 5. A comparison between the amount of particles that were collected during the simulation of four different wire configurations. A high collection percentage corresponds to a higher effectiveness with respect to the quality of air filtration.

III. Results

We can roughly define the efficiency of an electrostatic precipitator as the ratio of particles entering and exiting the device. In figure 5, we compare the efficiencies of four separate discharge electrode configurations using simulations of 100 evenly spaced particles. We ensure consistency by using the same initial particle positions for each "trial."

In these simulations, the majority of the particles became ionized by the corona of the first discharge electrode. This may be an artifact of the assumption that any particle that enters the breakdown region instantly acquires a negative charge. Consequently, the addition of multiple wire electrodes does not significantly affect the number of uncharged particles that become ionized; the varied configurations merely altered the migration paths of the charged particles. According to these results, the amount of negative electrodes in an electrostatic precipitator is not as important as the specific arrangement of the wires.

IV. Conclusion

The results of our investigation into the efficiency of wire placement in electrostatic precipitators provide an unexpected conclusion that may lead to more cost-efficient device designs with regard to energy or material consumption. However, given the significant assumptions we made to simplify the simulation process, there is a need for future research into this field. For example, using Laplace and potential to calculate the electric field would more accurately match the real-world behavior of conductors than the current use of electrostatics.

References

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