Laboratory Analysis of an Electrostatic Dust Collection System

K. A. Rosentrater

Department of Engineering and Industrial Technology
Northern Illinois University, DeKalb, IL, 60115, USA
Phone: (815) 753-9932; Fax: (815) 753-3702; Email: krosen@ceet.niu.edu

ABSTRACT

An electrostatic precipitator dust collector was investigated to determine the strength of the electromagnetic field between the system's discharge and collection electrodes, as well as the collector's ability to remove airborne particles. The system was tested in a laboratory chamber utilizing water-based aerosol particles to simulate dust particulates. The developed electromagnetic field behaved in a nonlinear fashion: field strength decreased exponentially with horizontal distance from the centerline of the collector, but varied quadratically with vertical distance from the collection electrode, with the maximum field strength occurring near the discharge electrode. Furthermore, for all coordinate directions examined, field strength increased as applied voltage potential between the electrodes increased. Additionally, this system reduced airborne particle concentrations exponentially, and produced removal rates between 8 and 13 times greater than gravitational settling alone.

Keywords
Dust Collector, Dust Control, Dust Extractor, Electromagnetic Field, Electrostatic Precipitator, Evaluation

INTRODUCTION

Dust, a major challenge in modern livestock operations, originates from multiple sources, including dry animal skin, hair, feces, and feed particles (Bundy, 1989; Donham and Gustafson, 1982). Its behavior is influenced by many environmental factors, including air temperature, humidity, flow rate, type and amount of feed provided, and animal activity level (Butera et al., 1991; Dawson, 1990; Heber and Stroik, 1987; Predicala et al., 2001; Qi et al., 1992). Many studies have quantified dust levels in livestock housing, especially in swine facilities. Heber and Stroik (1987) investigated 11 commercial swine finishing units and found total aerial dust concentrations ranging from 212,000 to 73,550,000 particles/m^3, with an average level of 11,209,000 particles/m^3. Honey and McQuitty (1979) investigated aerial dust levels in a chamber that simulated a swine environment and found an average total dust concentration of 5,160,000 particles/m^3. Numerous studies have also examined mass concentrations of airborne swine dust, and have found levels ranging from 0.36 to 38.2 mg/m^3 (Heber and Stroik, 1987), 1.0 to 100.0 mg/m^3 (Carpenter, 1986), 1.2 to 6.7 mg/m^3 (Donham and Gustafson, 1982), 2.4 to 16.0 mg/m^3 (Popendorf and Donham, 1991), 6.3 to 7.6 mg/m^3 (Donham et al., 1986), and 10.0 to 20.0 mg/m^3 (Mutel et al., 1986).

It has been estimated that over 700,000 people in the United States are exposed to hazardous levels of swine dust each year, and over 60% of these suffer from various respiratory disorders, including organic toxic dust syndrome, chronic bronchitis, hypersensitivity pneumonitis, and occupational asthma (Donham and Gustafson, 1982; Donham, 1999; Mutel et al., 1986; Popendorf and Donham, 1991). These primarily include confinement workers, but also family members of these workers and veterinarians (Donham and Gustafson, 1982). Swine dust particles are hazardous to human health because a substantial portion is smaller than 5 μm in diameter, and are thus "respirable", because their small size allows for significant deep lung penetration, deposition, and consequent accumulation (Bundy and Hazen, 1973; Dorman, 1974).

Dust can also produce other problems, including adverse health effects in the swine themselves, because the physical size and shape of the dust particles, as well as the gas molecules that have been adsorbed from the air (e.g., ammonia, hydrogen sulfide, and carbon dioxide) can cause airway irritation and respiratory disease, especially pneumonia (Takai et al., 2002). It has been estimated that between 35 and 60% of all swine raised in confinement conditions suffer from pneumonia (Chiba et al., 1987). Additionally, dust can carry and promote large aggregations of microorganisms, including viruses and bacteria (both gram-positive and gram-negative), especially Salmonella, Staphylococcus, Micrococcus, Endotoxin, and Rotavirus (Bundy, 1989; Butera et al., 1991; Donham, 1991; Fu et al., 1989; Mitchell et al., 2004; Thorne et al., 1992). Dust also harbors odorous substances, such as volatile fatty acids, phenols, and carbonyl compounds (Bundy and Hazen, 1975; Hammond et al., 1981; Heber et al., 1988). Furthermore, swine dust can accelerate the deterioration of the buildings themselves and of the mechanical components housed within. In combination with high humidity levels, which are typically found in swine environments, swine dust deposits on, and causes abrasion to, all exposed surfaces in a swine facility, and thus accelerates the corrosion process (Bundy and Hazen, 1973; Davis and Cornwell, 1991). Moreover, dust can severely impair the performance of ventilation systems by accumulating on timers, thermostats, fans, motors, vents, ducts, and shutters, and can either cause these components to perform poorly or to fail completely (Carpenter, 1986). These production issues are not isolated to swine housing alone, but in fact, exist in all livestock environments.

Thus, there is a need to develop an efficient, practical, and inexpensive method of dust removal for these environments. One technique that can be used to accomplish this is electrostatic precipitation. Electrostatic collectors are devices that impart electric charges to dust particles and then push them out of the air stream using electromagnetic forces. They typically exhibit low operating costs, and high removal efficiencies, for a wide range of particle sizes, and thus offer much potential to effectively extract dust particles from livestock housing systems. Several studies have examined electrostatic precipitator performance in swine environments. Bundy and Hazen (1974) found that electrostatic ionization could produce airborne swine dust removal rates up to six times greater than gravitational sedimentation alone. Bundy and Veenhuizen (1987) determined precipitator efficiency by measuring dust concentrations (using simulated dust particles) upstream and downstream from the air cleaner itself, and achieved a 90% particle reduction. Veenhuizen (1989) determined collection efficiencies by measuring swine dust concentrations in room air where precipitators were used as internal air cleaners, and attained a 54% in reduction in overall dust levels. Rosentrater (2003) achieved up to 58% reduction in airborne swine dust concentrations in rooms where precipitators were utilized. Mitchell et al. (2004) achieved a 61% reduction in overall dust levels in poultry broiler housing using an electrostatic system.

Even though research has shown that electrostatic precipitators can reduce dust levels substantially, an optimal design for use in livestock facilities has not yet been fully developed. Therefore, the objectives of this study were to examine an electrostatic precipitator system, both in terms of electromagnetic field strength, as well as ability to reduce airborne particle concentrations over time, and as such, quantify the resulting particle removal rates, and thus determine the operational performance of the collector.

MATERIALS AND METHODS

The electrostatic precipitator used in this study (Figure 1) was identical to that used by Rosentrater (2003). It consisted of a discharge electrode, which was constructed from a single strand of 0.3 mm (0.01 in.) diameter stainless steel wire, and a grounded collection electrode, which was fabricated from a 10.2 cm (4 in.) diameter steel pipe, which was positioned 17.8 cm (7 in.) below the wire. The discharge wire and the collection pipe were supported by 6.4 mm (0.25 in.) thick PVC end plates. A dust collection tray, installed under the pipe, was constructed from one-half of a 20.3 cm (8 in.) diameter, 3.2 mm (0.13 in.) thick, PVC pipe cut longitudinally. Additionally, an ionization guard was located above the wire, to direct electrons and charged dust particles down toward the collection electrode, and consisted of one-half of an 8.9 cm (3.5 in.) diameter, 3.2 mm (0.13 in.) thick, PVC pipe cut longitudinally. The entire unit was 3.05 m (10 ft) in overall length. To charge the precipitator, and provide negative ionization at the discharge wire (which imparts electrical charges to passing dust particles), the electrode wire was connected to a -20 kV, 50 mA, rectified a.c. power supply unit.

Prior to testing, the precipitator unit was suspended from the center of the ceiling of a fully sealed, 4.7 m (15.5 ft) long, 3.5 m (11.6 ft) wide, 2.4 m (8.0 ft) high test chamber, of which the walls and ceiling consisted of painted drywall surfaces and the floor was concrete. Electromagnetic field strength was measured using a handheld Gauss meter (Model HHG-14, Omega Engineering, Stamford, CT), which had a measurement range of 0.1 to 199.9 mG, a frequency response range of 20 to 2000 Hz, and an accuracy of ±1%, positioned at various horizontal and vertical locations (Figure 2). Horizontal distance from the precipitator's centerline included seven locations that were each subsequently 5.08 cm (2 in.) apart, up to a total distance 35.6 cm (14 in.) from the centerline. Vertical distance, which was also measured in 5.08 cm (2 in.) gradations, originated at the top face of the collection electrode, and included four locations below this plane (20.3 cm [8 in.]), and 11 locations (55.9 cm [22 in.]) above this plane; this ultimately resulted in a total vertical span of 38.1

cm (15 in.) both above and below the discharge electrode that were analyzed. Throughout this phase of the study, the applied voltage potential between the electrodes was varied between -4 and -20 kV, in 2 kV increments, by use of a variable transformer connected to the discharge electrode. Each experiment was replicated three times, and all collected data were subsequently subjected to regression analysis to quantify the voltage-position relationships that were observed.

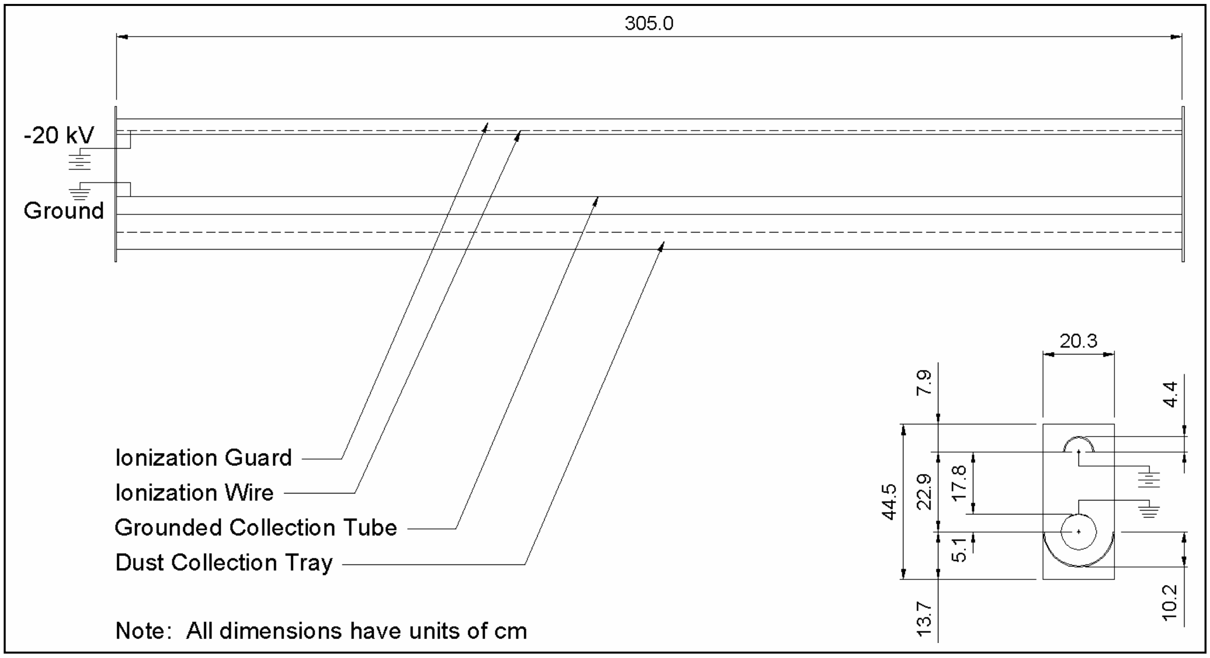

Figure 1. Schematic of electrostatic precipitator unit.

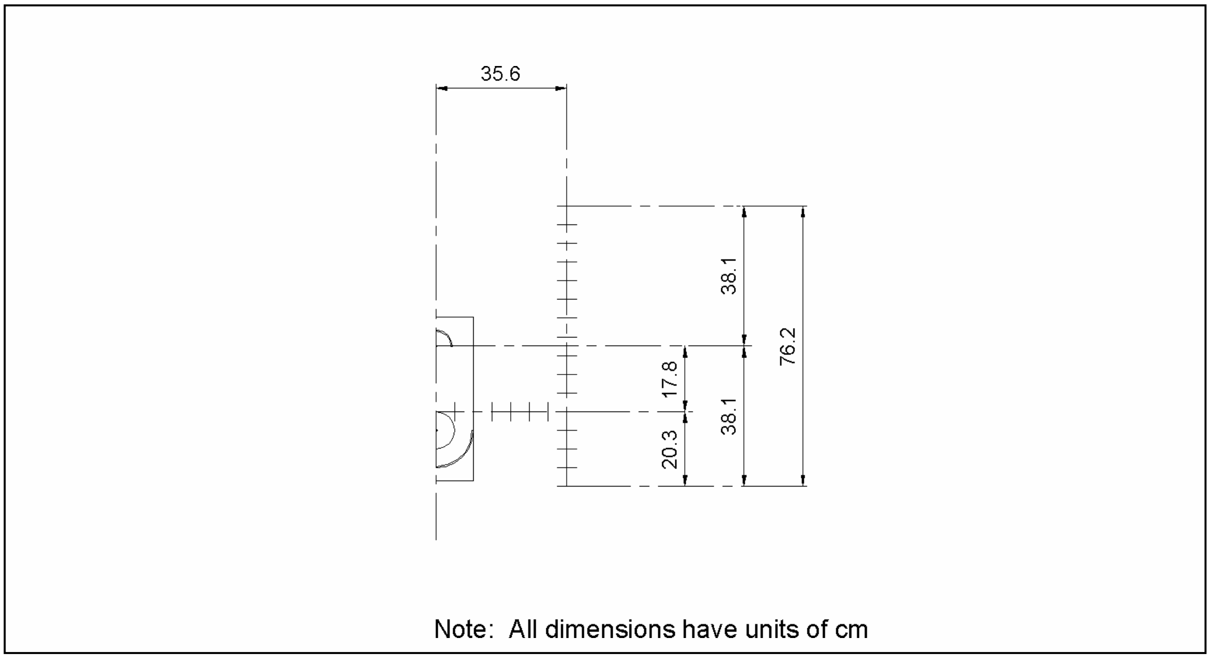

Figure 2. Schematic of electromagnetic field strength measurement locations.

The next phase of the study entailed testing the ability of the electrostatic precipitation system to remove airborne particles. Dust particles were simulated using aerosolized water droplets, which were produced using compressed air via a fogging device (Model Burgess 960, Fountainhead Group, New York, NY), which produced aerosol particles with an average aerodynamic diameter of 15 µm, for five minutes prior to experimentation. The test chamber environment was then monitored by measuring aerosol levels with a laser particle counter (Model 200, Met One, Inc., Grants Pass, OR). This device utilized six separate sampling channels, and could simultaneously measure all airborne aerosol particles with aerodynamic diameters down to, and including, 0.3, 0.5, 1.0, 2.0, 5.0, and 10.0 µm, and operated with a sampling flow rate of 4.72×10^{-5} m^3/s (0.1 $ft^3/min.$). To measure concentrations, the counter was placed in the center of the chamber, with the sample port, which was located on the top side of the machine, facing upward, and was positioned 1.3 m (4.3 ft) above the floor. This positioning allowed for the concurrent measurement of particulate levels in a location that was representative of the intersection between the breathing zones of both humans and animals, and is a method that has been used previously by

Barber et al. (1991), Bundy and Hazen (1973), and Butera et al. (1991). Readings were taken every five minutes, for a total of 80 minutes, during each experiment. Throughout this phase of the study, the applied voltage potential between the electrodes was varied, by use of a variable transformer connected to the discharge electrode, and was set at 0 (i.e. gravitational settling only), -8, -15, and -20 kV. Each experiment was replicated three times, and all collected data were subsequently subjected to regression analysis to quantify the voltage-time relationships that were observed.

RESULTS AND DISCUSSION

Electromagnetic field strength results for the horizontal locations studied are shown in Figure 3, which summarizes the findings via nonlinear regression curves that were developed utilizing the exponential model provided in Equation 1, which, upon statistical analysis, was found to provide the best statistical fit to the collected data.

$$y = A \cdot e^{n \cdot x} \tag{1}$$

Table 1, which summarizes the consequent regression parameters for all voltage levels used, reveals that electromagnetic field intensity decreased exponentially as horizontal distance from the collector's centerline increased, but increased as applied voltage potential was increased. These trends agree with the nonlinear behavior described for other electrostatic precipitator systems (Ogawa and Beddow, 1984; Batel, 1976). Furthermore, the data exhibited moderate to low variability, and the regression curves had coefficient of determination (R^2) values ranging from approximately 0.79 to 0.99.

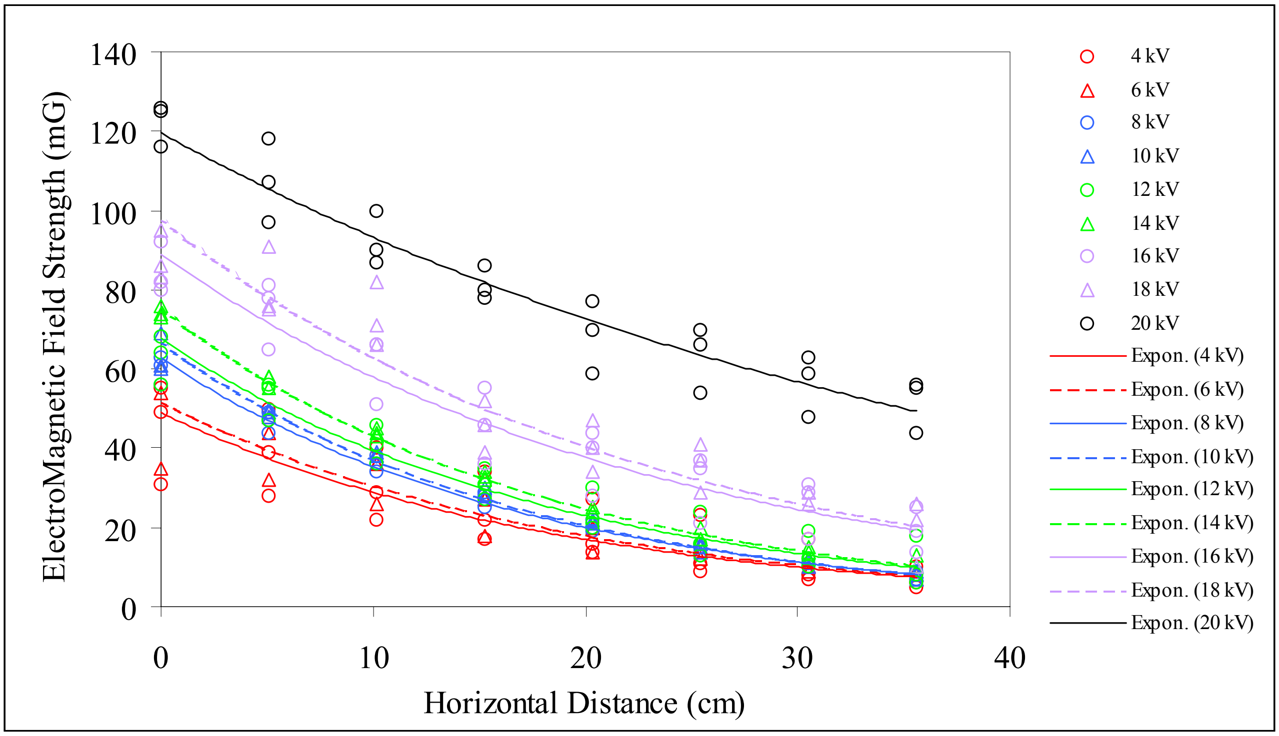

Figure 3. Horizontal electromagnetic field intensity results.

Table 1. Regression indexes for horizontal electromagnetic field intensity.

Voltage (kV)	A (mG)	n (cm^{-1})	R^2 (-)	St Dev (mG)
4	48.967	-0.053	0.795	8.003
6	51.895	-0.053	0.929	5.040
8	62.700	-0.057	0.988	1.907
10	66.884	-0.059	0.990	5.299
12	67.589	-0.054	0.879	1.425
14	75.304	-0.055	0.989	6.572
16	89.006	-0.043	0.870	1.354
18	97.853	-0.044	0.864	7.903
20	119.520	-0.025	0.907	7.351

Electromagnetic field strength results for the vertical locations studied are shown in Figure 4, which summarizes the findings via nonlinear regression curves that were developed utilizing the quadratic model provided in Equation 2, which, upon statistical analysis, was found to provide the best statistical fit to the collected data.

$$y = A \cdot x^2 + B \cdot x + C \quad (2)$$

Table 2 summarizes the consequent regression parameters for all voltage levels used. Electromagnetic field intensity varied quadratically as vertical distance from the collection electrode's top surface increased, with the maximum field intensity occurring near the discharge electrode. Field strength also increased as applied voltage potential was increased. These trends agree with the nonlinear behavior described for other electrostatic precipitator systems (Ogawa and Beddow, 1984; Batel, 1976). Moreover, the data exhibited moderate to low variability, and the regression curves had coefficient of determination (R^2) values ranging from approximately 0.69 to 0.92.

Figure 5 summarizes the airborne particle removal performance via nonlinear regressions curves that were developed utilizing the exponential model provided in Equation 1, which, upon

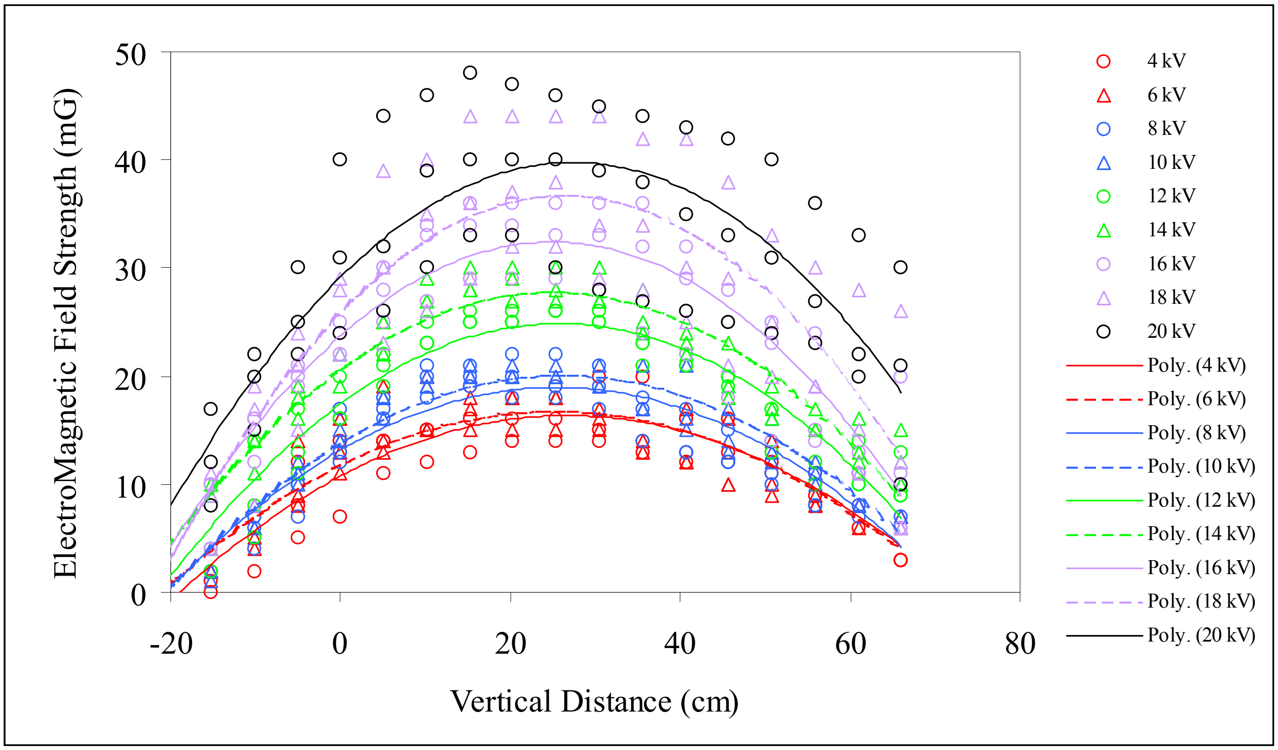

Figure 4. Vertical electromagnetic field intensity results.

Table 2. Regression indexes for vertical electromagnetic field intensity.

Voltage (kV)	A (mG/cm^2)	B (mG/cm)	C (mG)	R^2 (-)	St Dev (mG)
4	-0.008	0.419	10.763	0.800	2.293
6	-0.008	0.395	11.772	0.835	1.882
8	-0.009	0.455	13.163	0.853	1.709
10	-0.009	0.484	13.799	0.924	1.299
12	-0.011	0.575	17.440	0.906	1.746
14	-0.011	0.575	20.616	0.907	1.850
16	-0.014	0.696	23.724	0.838	3.948
18	-0.015	0.824	25.868	0.753	6.580
20	-0.014	0.776	29.171	0.688	7.187

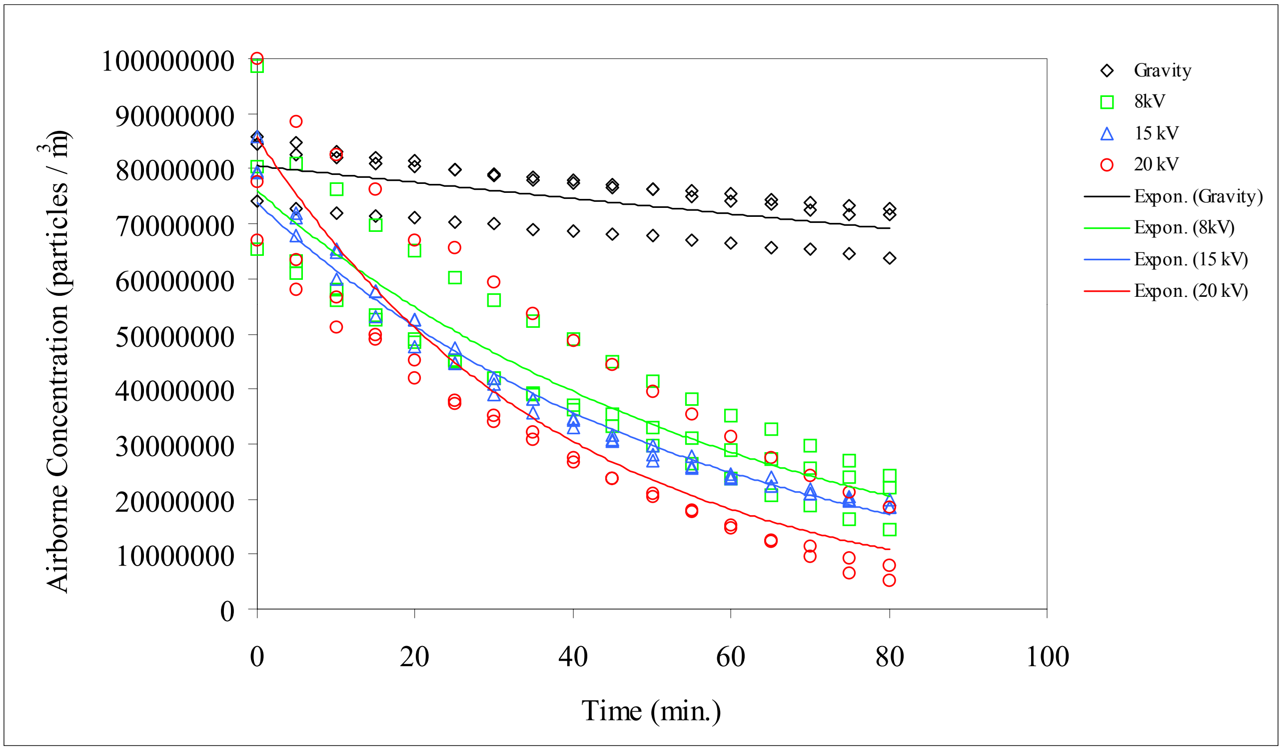

Figure 5. Particle concentration decay results.

statistical analysis, was found to provide the best statistical fit to the collected data. Table 3 summarizes the consequent regression parameters for all voltage levels used. At the sampling location used, gravitational settling alone produced a very low rate of particle removal (which could be quantified via n in Equation 1). Use of the electrostatic precipitator, in addition to gravitational setting, which was, in fact, still in effect during precipitator operation, greatly increased the rates of particle removal compared to gravitational settling alone, with an applied voltage potential of -8 kV resulting in a removal rate eight times greater than gravitational settling alone, -15 kV resulting in a removal rate nine times greater, and -20 kV resulting in a removal rate 13 times greater. As the results also show, the data exhibited moderate variability, and the regression curves had coefficient of determination (R^2) values ranging from approximately 0.79 to 0.98. The resulting curve for gravitational settling, however, exhibited a coefficient of determination value of approximately 0.39, which, although the line actually fit the data well, was essentially produced because the curve was approaching horizontal (which, by definition, has an R^2 value of 0).

Table 3. Regression indexes for particle concentration decay.

Voltage (kV)	A (particles/m^3) x 10^7	n (min^{-1})	R^2 (-)	St Dev (particles/m^3) x 10^6
0	8.053	0.002	0.386	5.295
8	7.604	0.016	0.862	7.972
15	7.382	0.018	0.983	1.517
20	8.573	0.026	0.793	12.271

CONCLUSIONS

When examining the results obtained by subjecting the electrostatic precipitator unit to laboratory testing, the following conclusions can be drawn:

1. The electromagnetic field intensity that developed between the discharge and collection electrodes behaved nonlinearly, and varied according to vertical and horizontal position with respect to the electrode geometry, and increased as applied voltage was increased.
2. As applied voltage was increased, the resulting aerosol particle removal rates increased compared to gravitational settling alone.
3. During this study, however, it became apparent that the ionization guard did not work well in constraining the electromagnetic field at either the level of the discharge electrode, or at higher locations. Thus, an improved method for directing the field is needed in order to prevent charged particles from accumulating on ceiling surfaces from which the collector is suspended.
4. Furthermore, although this study did quantify electromagnetic field intensity, it was limited to the locations that were selected for study. Thus, a full two-dimensional plane consisting of equally spaced grid points should be examined in order to fully quantify the electromagnetic field that develops between the discharge and collection electrodes.

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