

DUST CONTROL IN LIVESTOCK BUILDINGS WITH ELECTROSTATICALLY-
CHARGED WATER SPRAY

by

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B.S., King Faisal University, Saudi Arabia, 1986

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AN ABSTRACT OF A DISSERTATION

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Abstract

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A dynamic Faraday-cage sampler was developed for measuring the net charge-to-mass ratio of particles. The device involves collecting particles on a filter and measuring the charge induced. The sampler was calibrated and then used to measure the charge of dispersed particles (i.e., corn starch, NaHCO_3 , positively charged water spray, negatively charged water spray, and uncharged water spray). The corresponding net charge-to-mass ratios were -0.11 (SD=0.07), +0.20 (0.001), +7.24 (1.6), -6.47 (0.9), and -0.30 (0.12) mC/kg.

Characterization of dust in a swine building showed mean dust concentration of 0.89 (SD=0.45) mg/m^3 , geometric mean diameter of particles of 9.34 μm , and geometric standard deviation of 2.11. The Faraday-cage sampler was also used in the swine building; the net charge-to-mass ratio of particles was +0.68 mC/kg (SD=0.31 mC/kg).

The effectiveness of charged-water spray in reducing dust concentration was investigated in an experimental chamber. Test particles (i.e., corn starch, NaHCO_3) were dispersed into the chamber and then charged water was sprayed into the chamber. The charged-water spray was significantly more effective than either the uncharged-water spray or no water spray. The removal efficiency of the charged water spray (4 min spray duration, 120 mL/min), based on

mass, ranged from 88% to 92% for particles $\leq 10 \mu\text{m}$ equivalent aerodynamic diameter (EAD) and from 34% to 70% for particles $\leq 2.5 \mu\text{m}$ EAD. A model based on coagulation was used to predict the particle concentration after spraying of charged water. Predicted values of concentration and removal efficiency agreed well with measured values.

A prototype EAPWS was also developed. Laboratory and field evaluations of the EAPWS indicated that it had significantly higher particle removal efficiency than either the control (i.e., no water spray) or the uncharged wet scrubber.

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List of Symbols

a	Regression intercept
$A_{c,t}$	Total cross sectional area of all droplets per unit volume
b	Regression slope
B	Coagulation correction factor
C	Coulomb
C_{10}	Particle mass concentration at $t=10$ min (mg/m^3)
C_t	Particle mass concentration at time t (mg/m^3)
C_o	Observed (measured) particle mass concentration (mg/m^3)
C_p	Predicted particle mass concentration (mg/m^3)
C_c	Cunningham or slip correction factor
C_d	Drag coefficient
c	Capacitance (F)
c_c	Capacitance of the cage (F)
c_l	Capacitance of the connecting lines (F)
c_e	Capacitance of the electrometer (F)
D	Electric flux density (C/m^2)
D_d	Diffusion coefficient of the water droplet (cm^2/s)
D_p	Diffusion coefficient of particle (cm^2/s)
d_a	Equivalent aerodynamic diameter (μm)
d_p	Particle diameter (μm)
d_d	Droplet diameter (μm)
E	Electric field (V/m)
E_a	Radial electric field (V/m)
E_i	Induced field (V/m)
E_s	Ratio of swept out area to cross sectional area of the droplet
e	Elementary charge (C)
FB	Normalized fractional bias
F_d	Aerodynamic drag force (N)

F_e	Electrostatic force (N)
F_{EC}	Force due to the Coulomb attraction between a charged particle and an oppositely charged collector (N)
F_{EM}	Force due to the dipole attraction between a charged particle and the dipole that this charge induces on the neutral collector (N)
F_{EI}	Force due to the dipole attraction between the charged collector and the dipole induced upon the neutral particle (N)
F_{ES}	Force due to the space charge repulsion of the cloud of charged particles (N)
F_{EX}	Force due to the electrostatic repulsive force between two point charges of like sign (N)
F_{adh}	Adhesion force (N)
f	Fraction of dust remaining compared with the initial dust concentration
FS	Bias based on variance
g	Gravitational acceleration
GMD	Geometric mean diameter by mass of sample (μm)
GSD	Geometric standard deviation
H	Height (m)
i	Electric current (A)
IDC	Inhalable dust concentration (mg/m^3)
K	Coagulation coefficient (m^3/s)
K_O	Coagulation coefficient for monodisperse particles (m^3/s)
K_{12}	Coagulation coefficient of droplets with particles (m^3/s)
K_{dp}	Brownian coagulation coefficient between the water droplet and particle (m^3/s)
K_{exp}	Experimental coagulation rate coefficient (m^3/min)
K_{exp-m}	Experimental coagulation rate coefficient - based on mass ($\text{m}^3/\text{mg}\cdot\text{min}$)
K_n	Corrected coagulation rate coefficient (m^3/s)
k	Boltzmann constant = 1.38×10^{-23} N.m/K
MF	Mechanical forces (N)
MW	Molecular weight (kg/kg.mol)
m	Mass of particle (mg)
m_i	Average mass collected in the air inlet filters (mg)

m_o	Average mass collected in the air outlet filters (mg)
NMSE	Normalized mean square error
N_t	Number concentration of particles at time t ($\#/cm^3$)
N_o	Number concentration of particles at $t=0$ ($\#/cm^3$)
P	Atmospheric pressure (Pa)
Pe	Peclet number
Q	Point charge (C)
q	Net charge (C)
q_p	Charge of particle (C)
q_d	Charge of droplet (C)
q_N	Net charge-to-mass ratio (mC/Kg)
Q_l	Liquid flow rate (L/min)
R	Universal gas constant, 8314 J/kg.mol.K
R^2	Coefficient of determination
RDC	Respirable dust concentration (mg/m^3)
Re	Reynolds number
R_p	Radius of the particle (μm)
r	Distance between the particle and the droplet centers (m)
r_d	Radius of the droplet (μm)
S	Surface area of the sphere (m^2)
SD	standard deviation
Stk	Stokes number
STEL	Short term exposure limit
T	Absolute temperature (K)
TDC	Total dust concentration (mg/m^3)
TLV	Threshold limit value (mg/m^3)
TWA	Time weighted average
T_p	Total time of aerosol precipitation
t	Time (s)
U_o	Air velocity (m/s)
V	Applied voltage (V)

v_d	Droplet velocity (m/s)
X_o	Maximum initial offset of the particle from the droplets axis

Greek symbols

α	Correction factor to account for the effects of mechanical and electrostatic forces
ε_a	Permittivity of air, 8.85×10^{-12} F/m
ε_0	Permittivity of the free space (F/m)
η	Collection (removal) efficiency
η_{10}	Removal efficiency for particles $\leq 10 \mu\text{m}$
$\eta_{2.5}$	Removal efficiency for particles $\leq 2.5 \mu\text{m}$
η_t	Removal efficiency for total suspended particles
η_{SC}	Overall removal efficiency of scrubber
η_{DI}	Single droplet collection efficiency due to direct interception
η_{IT}	Single droplet collection efficiency due to inertial impaction
η_G	Single droplet collection efficiency due to gravitational settling
η_{BD}	Single droplet collection efficiency due to Brownian deposition
λ	Mean free path of gas molecules (μm)
μ	Dynamic viscosity (kg/s-m)
μm	Micrometer
ρ_a	Air density (kg/m^3)
ρ_p	Particle density (kg/m^3)
ρ_g	Gas density (kg/m^3)
τ	Time constant (s)
χ	Shape factor of particle
ω	Particle velocity (m/s)

CHAPTER 1 - INTRODUCTION

1.1 Background

The constant change in agricultural practices has influenced the design and operation of farm buildings to a considerable level. Improved breeding, feeding, and health care have increased animal production. These developments have required larger livestock buildings designed for the specific needs of the animals housed. This means that modern livestock buildings must be designed for maximum efficiency, comfort, and safety. The last few decades have witnessed the shift from the small multipurpose farm with a barn housing cows, horses, sheep, pigs, and chickens plus hay and grain, to large single enterprise operations (Whitaker, 1979).

Poor air quality is a growing concern in livestock confinement buildings. A growing body of literature has documented the health problems among workers in these operations. Donham (1999), for example, reported the following statistics on swine confinement workers:

- At least 60% of workers surveyed have acute or subacute respiratory symptoms, including dry cough, chest tightness, and wheezing on exposure to the work environment; irritation of the nose, eyes, and throat; and stuffy nose and throat.
- At least 25% of the workers surveyed have periodic, acute, febrile episodes with fever, headache, muscle aches, and pains, chest tightness, and cough.
- At least 25% of the workers surveyed experience chronic bronchitis, occupational (nonallergenic) asthma, and noninfectious chronic sinusitis.

Air quality in livestock buildings should be improved to prevent occupational health problems. Engineering control strategies include the following: (1) reducing emission or generation rates of the air contaminants (i.e., source control); (2) dilution and/or effective room air distribution (i.e., ventilation control); and (3) air cleaning (i.e., removal control). Source control strategies for dust include use of feed additives (fats or oils), cleaning of dusty surfaces, and spraying water or oil over dusty surfaces. Ventilation control includes increasing ventilation rate, purge ventilation, and effective room-air distribution systems. Air cleaning strategies include use of air filters, ionizers, or wet scrubbers. Dust reduction efficiencies reported with these strategies have ranged from 15% for weekly washing of pigs and floors, to 23% with ionizers, to 76% with a rapeseed oil spray (CIGR, 1994). Other studies (Carpenter, 1986; Madelin and Wathes, 1988) have shown that reducing airborne dust levels by 50% can reduce airborne bacteria by 100-fold or more.

A potential dust reduction method is spraying charged water droplets into the airspace. Hoenig (1977) and Gillespie (1955) have shown that most dust particles acquire electric charges as they are dispersed into the air. The polarity and magnitude of the charges on these particles depend upon their size and origin (Hoenig, 1977; Hassler and Birgitta, 1978). Therefore, particle collection efficiency of water droplets can be significantly enhanced via the electrostatic forces of attraction if the droplets are charged to the opposite polarity (Mathai, 1983). As a result, increasing the electrostatic force of the water droplet can dramatically increase the collection of particles, even for small particles.

The principle of electrostatics has been applied to air cleaning technology. The following summarizes the development of electrostatics and its application to air cleaning.

- The principle of electrostatics, as discovered by Coulomb in 1785, was first successfully applied to the control of particulate pollutants by Cottrell in 1908 (White, 1963). Since then various kinds of gas cleaning devices, which are enhanced by electrostatics, have been developed.
- Penney (1944) proposed an electrostatic droplet spray scrubber consisting of charged water droplets for collecting aerosol particles charged to the opposite polarity.
- Pilat et al. (1970, 1974) showed an improvement in collection efficiency by charging the droplets and the particles to opposite polarities.
- Melcher et al. (1977) produced an overview of electrostatic devices for control of submicrometer particles, where particular emphasis was laid on the basic work on charged air pollution control devices. An evaluation of four particle collection devices was carried out by Calvert et al. (1978), and a number of commercial designs of electrostatic spray scrubbers are discussed by Allen (1982) and Xiao (2000).

While significant developments have occurred on electrostatic air cleaning, limited research has been conducted on its application to livestock buildings. Air ionizers have been used and tested in animal buildings (Czarick et al., 1985; Veenhuizen and Bundy, 1990; Mitchell, 1998). Measured dust collection efficiencies ranged from 31% (Czarick et al., 1985) to 92% (Mitchell, 1998). No published research has dealt with charged water spray in livestock buildings.

1.2 Research Objectives

The overall objective of this study was to evaluate the potential of electrostatically charged water droplets in controlling dust in livestock buildings. Specific objectives were to:

1. Develop a device for measuring the net charge-to-mass ratio of particles and water droplets;
2. Characterize the size distribution and electrostatic charge of dust particles in a livestock building;
3. Evaluate the effectiveness of charged-water spray in controlling dust concentration in enclosed airspaces, as a function of the magnitude and polarity of charge, and spray duration;
4. Model the performance of electrostatically charged water droplets in controlling dust particles; and
5. Develop and evaluate an air cleaning device that uses charged-water spray.

1.3 Organization of the Dissertation

This dissertation has eight chapters and an Appendix. Sections 1.1 and 1.2 of this chapter have stated the rationale and the objectives of this research. Chapter 2 reviews the previous work related to this research. It presents background information on dust as a major pollutant in livestock buildings, various methods of dust control, charge measurement techniques, and charged water spray.

Chapters 3, 4, 5, 6 and 7 address specific objectives 1, 2, 3, 4, and 5, respectively. Chapter 3 presents the development and evaluation of the charge measurement device. Chapter 4 deals with the characterization of airborne particles in a swine finishing building. Chapter 5 deals with the laboratory research to test the effectiveness of charged water spray in reducing dust concentration in an enclosed airspace. Chapter 6 presents a model to predict dust concentration and removal efficiency of charged water spray. Chapter 7 studies the application of charged water spray in cleaning the air in livestock buildings using wet scrubber.

Chapter 8 provides a summary, conclusion, and recommendations for future work. The Appendix contains a summary of information on electrostatically-charged water spray, including characterization and principles of charging water droplets, and experimental data.

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CHAPTER 2 - LITERATURE REVIEW

2.1 Agricultural Buildings and Structures

Buildings are an integral part of modern agriculture and contribute greatly to the efficiency of operation, the quality of the products, and the health and comfort of workers and livestock (Lindley and Whitaker, 1996). According to Sloane (1966), "The successful farmer has been transformed into a businessman and the barn has become a factory." Agricultural buildings have changed over the years as differing requirements have been imposed and new methods and materials have been developed.

The constant change in agricultural practices has influenced the design of farm buildings to a considerable degree. For example, improved breeding, feeding, and health care have increased animal production. These developments have required larger livestock buildings designed for the specific needs of the animals housed. This means that livestock buildings must be designed for maximum efficiency, comfort, and safety. The last few decades have witnessed the shift from the small multipurpose farm with a barn housing cows, horses, sheep, pigs, and poultry plus hay and grain, to large single enterprise operations (Whitaker, 1979).

2.2 Air Contaminants in Livestock Buildings

The increase in intensive livestock production system has resulted in the generation, accumulation, and disposal of large amounts of wastes. Generation of particulate and gaseous pollutants is an inevitable consequence of the generation and handling of the wastes. These pollutants influence the quality of the air in and around livestock buildings. Air quality inside

the building can affect human and animal health and welfare, while air pollutant emissions from the buildings can lead to local and even global environment pollution (Hinz and Linke, 1998). Table 2-1 summarizes the suggested threshold limit values (TLVs) for gaseous and particulate contaminants.

Table 2-1 Threshold limit values (TLV) for gaseous and particulate contaminants.

Air Contaminant	TLV-TWA ^a	TLV-STEL ^b	Max-Human ^c
Carbon dioxide (CO ₂)	5,000 ppm	30,000 ppm	1,500 ppm
Ammonia (NH ₃)	25 ppm	35 ppm	7 ppm
Hydrogen sulfide (H ₂ S)	10 ppm	15 ppm	5 ppm
Carbon monoxide (CO)	25 ppm	-	50 ppm
Nuisance/airborne dust	10 mg/m ³	-	2.4 mg/m ³
Respirable dust	5 mg/m ³	-	0.23 mg/m ³
Endotoxin	-	-	800 IU/ m ³

^aTLV-TWA: Threshold limit value for time weighted average exposure concentration for a normal 8 to 10 h workday (ACGIH, 1993).

^bTLV-STEL: Short term exposure limit, i.e., 15 min time-weighted average exposure limit for any time during a workday (ACGIH, 1993).

^cRecommended maximum levels for human health (Donham, 1987; Donham et al., 1989).

2.2.1 Gaseous contaminants

Gaseous contaminants from livestock buildings may include greenhouse gases that can contribute to global warming, gaseous contaminants that can cause adverse health effects, and volatile organic compounds (VOCs) that are closely associated with nuisance odors. Although all of these gases are potentially hazardous to humans and animals, they are generated at varying rates such that some are of greater concern than others (Predicala, 2003). The major gaseous contaminants of concern in livestock buildings include NH₃, H₂S, methane (CH₄), CO₂, CO, and VOCs.

Ammonia (NH_3) is released primarily from the decomposition of nitrogenous compounds in manure and urine. It is an irritant when it comes in direct contact with mucous membrane in the respiratory tract and may be also be fatal at elevated concentrations (DeBoer and Morrison, 1988).

Hydrogen sulfide (H_2S), a colorless gas, is produced from the putrefaction of organic wastes. It has a pungent odor characteristic of rotten eggs. Heavier than air, it would tend to stay near the floor in non-ventilated, quiescent rooms. It is a highly toxic gas and has caused numerous deaths in human and livestock when acute levels were generated under certain conditions (Patni and Clarke, 1991). It may also cause adverse health effects (i.e., irritation, headache, dizziness) even at concentration as low as 10 ppm (DeBoer and Morrison, 1988).

Methane (CH_4), a colorless and odorless gas, is produced from anaerobic decomposition of manure. Although it is not considered a toxic gas, it is highly flammable and can cause a dangerous explosion when allowed to reach concentrations of 5,000 to 150,000 ppm and ignited (Taiganides and White, 1969). As a greenhouse gas, it is estimated to contribute about 18% of total global warming potential (Murray et al., 1999). In livestock systems, ruminant digestive activity, manure decomposition, and silage fermentation are considered as the main sources of CH_4 , accounting for 29% of total annual CH_4 emissions in the U.S. (EPA, 1999).

Carbon dioxide (CO_2) is found in the atmospheric air, with a concentration of approximately 350 ppm on volume basis. In animal confinement buildings, CO_2 is released from biological decomposition of manure and from the air exhaled by animals. High concentrations of CO_2 may be caused by poor ventilation and improperly vented fuel-burning heaters, which may also give rise to CO, another potentially hazardous gas. At very high concentrations, CO_2

can asphyxiate humans and animals by reducing the amount of oxygen present (De Boer and Morrison, 1988).

Volatile organic compounds (VOCs) and odorous gases are generated by the biological decomposition of livestock manure. Each of these compounds, 168 of which were listed by O'Neill and Phillips (1992), may occur only in trace amounts and generally is not found at levels considered hazardous to human and animal health. Their combined effects, however, are responsible for unpleasant odors associated with animal facilities (Mackie et al., 1998). The emission and transport of these compounds over long distances during certain atmospheric conditions have caused serious conflicts between animal farmers and concerned neighbors, initiating concerted efforts to quantify and control odors from animal production facilities (Predicala, 2003).

2.2.2 Particulate contaminants

Airborne particulate contaminants inside animal buildings may include organic and inorganic dust, as well as bioaerosols, both of which had been implicated as responsible for respiratory symptoms observed in exposed workers and animals (Donham et al., 1989; Donham, 1993). Airborne dust also contributes to the deterioration of buildings and equipment (Phillips and Thompson, 1989) and can carry odorous compounds (Day et al., 1965; Burnett, 1969) and pathogens (Muller and Wieser, 1987).

In livestock buildings, dust can be generated from feed, manure, animal dander or feathers, litter material, and building components through animal activity and husbandry operations (Takai et al., 1998). Airborne dust particles, being derived from various organic and inorganic sources, can be potentially irritating and allergenic. Organic dust has been implicated as a cause of work-related symptoms such as asthma, organic dust toxic syndrome, and chronic

bronchitis in farm workers (Donham, 1993). Dust particles may also carry bacteria and viruses, thereby potentially transporting harmful pathogens within and between animal housing environments (Muller and Wieser, 1987). Particulate emissions from livestock buildings have historically been categorized as fugitive emissions; these are not considered in the inventory of emissions required to classify a facility as a major stationary source (i.e., emitting more than 100 tons/yr of any regulated pollutant). However, the known ill-health effects of organic dust from animal buildings and their potential to transport harmful materials such as adsorbed odorous and irritant gases and microorganisms call for careful monitoring of the emission and dispersion of particulates from animal buildings (Predicala, 2003).

2.2.2.1 Sources and composition

Major sources of dust in livestock buildings include the feed, animals, manure, bedding materials (if present), and outside air. Hartung (1986) has estimated that about 80-90% of the dust in animal houses comes from feed, 2-12% from animals, 2-8% from manure, and a certain portion from bedding materials. A comprehensive analysis of the dust from swine houses identified feed (starch granules, grain meal, trichomes, and corn silk); fecal material (bacteria, gut epithelial cells, and undigested feed); dander; mold (hyphae, spores, and sporangia); pollen; insect parts; and mineral ash (Donham et al., 1986). The predominant components were feed among particles larger than 5 μm in diameter, and fecal material among particles between 1 and 2 μm in diameter. Airborne dust in finishing units was coarse and tannish. It was also fluffier than dust from farrowing, nursery, and growing buildings because of higher quantities of feed used in the finishing units. The respirable fraction was primarily fecal material, probably generated by animal movements (Donham et al., 1986).

Honey and McQuitty (1979) indicated both airborne and settled dust particles in swine buildings were primarily feed particles. Analysis of the photomicrographs of dust particles with diameters of 11 to 16 μm indicated that about 1 and 10% were hair and skin, respectively. In addition, skin comprised 5 % of the 7 to 9 μm particles.

Several researchers noted that many large airborne particles were actually agglomerates of smaller particles caused by electrostatic attraction (Koon et al., 1963) and the attachment of viruses and bacteria (Harry, 1978).

2.2.2.2 Particle size and size distribution

The size of particles influences their sedimentation rate (Janni et al., 1984) and the location of their deposition in the respiratory tract (Mercer, 1978). Dust particles greater than 10 μm in diameter usually settle out of the air rapidly (DeBoer and Morrison, 1988) and, if inhaled are trapped in the nose and throat; particles from 5-10 μm in diameter will reach the windpipe and those less than 5 μm in diameter may reach the bronchioles and alveoli. The size of the particle also influences its ability to pass through filters (Carpenter et al., 1986a). The 5 to 20 μm diameter particles are primarily responsible for the odor-carrying ability of airborne dust (Honey and McQuitty, 1979; Burnett, 1969). A majority of airborne bacteria adhere to particles larger than 4 μm (Robertson and Frieben, 1984). Viable particles may carry harmful microorganisms and endotoxins (Donham et al., 1986).

Particle size measurement is usually based on the dynamics of the particles and the size is usually expressed as the aerodynamic diameter, which is the diameter of a unit density sphere having the same settling velocity and, therefore, the same aerodynamic properties as the particle in question. The aerodynamic diameter has directional elements, but for particles of non-

isometric but relatively symmetrical shape these usually vary less than the physical dimensions of the particle (Horvath, 1974).

Numerous studies have measured the size and size distribution of airborne particles inside livestock buildings. Donham et al. (1986) reported a mean mass median diameter (MMD) of 9.6 μm and a geometric standard deviation (GSD) of 2.5 from four swine finishing facilities; respirable fractions were 20.1% from farrowing buildings, 13.4% from nursery-grower buildings, and 12.4% from finishing buildings. Maghirang and Puma (1997) found a MMD of 13 μm and a GSD of 3 from a mechanically ventilated swine nursery building, 11% of mean values of the total mass collected were respirable. Predicala et al. (2001) found that 79% and 80% of the particles measured were larger than 10 μm in the naturally ventilated (NV) and mechanically ventilated (MV) barns, respectively. Furthermore, mean values of the MMD and GSD for the NV barn were 17.9 μm and 2.2, respectively, and 18.1 μm and 2.1 for the MV barn, respectively.

2.2.2.3 Dust concentrations in livestock buildings

Numerous studies have also measured dust concentrations inside livestock buildings. Honey and McQuitty (1976) reviewed previous research and indicated that 14 cited sources gave a range of 1 to 100 mg/m^3 and that published data showed little or no consistency. In piggeries, the feeding system greatly affected dust levels (Bundy and Hazen, 1975) and, in a survey (Cermak, 1976), concentrations ranged from 0.5 to 79 mg/m^3 , the lowest values being associated with wet feeding and the highest with weaner houses. Another survey (Cermak and Ross, 1978) quoted a range of 0.2 to 400 mg/m^3 for background levels when stock were quiet at one extreme and close to a worker's face when feed was being handled at the other, while activities such as turkey weighing and egg collecting resulted in 40 mg/m^3 . A survey (ADAS Technical Services Division, 1981) of intensive poultry units recorded maximum values of 32 mg/m^3 for broilers on

litter, 18 mg/m³ for layers on litter and 6 mg/m³ for layers in cages. Records during the seven weeks of a commercial broiler crop (Moulsey, 1981) gave a range of 1.3 to 16.8 mg/m³.

Riskowski et al. (1995) reported that dust concentrations varied from <1 to 15 mg/m³ and can reach up to 100 mg/m³ during feeding times. A mean dust concentration of 8.1 mg/m³ was measured by Heber and Martin (1988) and 13 out of 88 measurements exceeded the OSHA recommendation. Furthermore, they observed that the naturally ventilated barns had significantly higher dust concentration than the mechanically ventilated barns. Donham et al. (1986) reported total mass concentrations of 3.2 mg/m³ from farrowing buildings, 5.2 mg/m³ from grower-finishing buildings, and 15.3 mg/m³ from finishing units. Predicala et al. (2001) reported inhalable and respirable dust concentrations of 2.19 and 0.10 mg/m³ from a naturally ventilated swine finishing barn, respectively, and 2.13 and 0.11 mg/m³ from a mechanically ventilated barn, respectively.

2.2.2.4 Dust as carrier of odor and microorganisms

Dust particles can adsorb and serve as carriers of vapors and odors (Hartung, 1986; Bundy and Hazen, 1975; Hammond et al., 1981; Heber and Martin, 1988). Noxious gases can adhere to the surface of aerosol particles, thus, increasing the gas concentrations several-fold (Janni et al., 1984). Donham et al. (1986) reported that about 3.9 mg of NH₃ gas was adsorbed on a gram of settled particulates. Several studies reported that filtration of the dust rendered the air nearly odorless (Burnett, 1969; Eby and Wilson, 1969; Hammond et al., 1979; Hammond et al., 1981). A report claimed that the 5-20 µm diameter particle size range was responsible for most odor transport (Honey and McQuitty, 1976). Aside from transporting the odor, the dust can also amplify the odor from livestock operations (Takai et al., 1998; Hammond et al., 1979); once

exhausted, the dust with the adsorbed odorants can travel great distances, after which the odors are then released from the particle over time.

Dust can carry and promote large aggregations of microorganisms, including viruses and bacteria (Bundy, 1989; Butera et al., 1991; Donham, 1991; Thome et al., 1992). In addition to the odorous compounds, dust also harbors endotoxin (Bundy and Hazen, 1975; Hammond et al., 1981; Heber and Martin, 1988).

2.2.2.5 Effects of airborne dust on worker and animal health

Dust can adversely affect the health of the people working in the livestock buildings (Parry et al. 1987; Dosman et al., 1988; Donham et al., 1989; Owen, 1994; Zejda et al., 1994; Senthilselvan et al., 1997a). In 1986, it was estimated that over 700,000 people in the U.S. were exposed to hazardous levels of swine confinement dust. Further, it has been estimated that over 70% of all of those who were exposed to confinement dust suffered from various respiratory disorders, including organic toxic dust syndrome, chronic bronchitis, hypersensitivity pneumonitis, and occupational asthma (Donham and Gustafson, 1982; Mutel et al., 1986; Popendorf and Donham, 1991). The people who were primarily exposed to swine dust included workers, family members of these workers, and veterinarians (Donham and Gustafson, 1982). The people most at risk for developing respiratory disorders, however, were those with long-term exposure to the dust (i.e., producers and other personnel who worked 8-h days for several years) (Mutel et al., 1986). Swine dust particles are hazardous to human health because a substantial proportion lies below 5 μm in diameter, and thus are respirable, because their small size allows for significant deep lung penetration, deposition, and consequent accumulation (Bundy and Hazen, 1973).

Inhaled airborne particles and microorganisms can cause adverse health effects, such as asthma and allergic diseases (Burge, 1990; Koskinen et al., 1995; Miller, 1992; Spengler et al., 1993) as well as airborne infections (Burge, 1990). Exposure to indoor aerosol pollutants has become a growing public and occupational health concern (American Lung Association, 1997; Gammage and Berven, 1996; Samet and Spengler, 1991).

The smaller particles are considered more dangerous to the health of workers or animals, because they can be inhaled much deeper into the respiratory tract (Schwartz, 1997). Particles of 1 μm in diameter or less can be inhaled into the alveolar sacs of the lungs. Reducing dust concentration within buildings has resulted in improvement in human respiratory responses (Senthilselvan et al., 1997b; Zhang et al., 1998).

For humans, the TLVs for inert mineral dust are 10 mg/m^3 for total dust and 5 mg/m^3 for respirable dust (Health and Safety Executive, 1980) (Table 2-1). Because of the variability of organic dust, no TLV for it is given and, the above values can therefore be regarded only as guidelines. Suggested exposure limits in swine confinement buildings are summarized in Table 2-2.

Airborne dust can also adversely affect the health of the animals inside the livestock buildings (Verstegen et al., 1994). In lactating animals, poor air and litter hygiene have been recognized to have a deleterious effect on milk yield (Sevi et al., 1998) and to predispose to mastitis infection (Bramley and Neave, 1975).

Table 2-2 Suggested exposure limits for workers and animals in swine confinement environments.

Air contaminant	Humans	Animals	Reference
Total dust, mg/m ³	2.4	3.7	Donham and Cumro, 1999
	-	3.4	Wathes, 1994
Respirable dust, mg/m ³	0.23	0.23	Donham and Cumro, 1999
	-	1.7	Wathes, 1994
Total endotoxin, EU*/m ³	614	1540	Donham and Cumro, 1999
Respirable endotoxin, EU/m ³	0.35	-	

* EU = endotoxin units

2.2.2.6 Effects of airborne dust on the buildings

Dust can accelerate the deterioration of buildings 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). In addition to contributing to the deterioration of the building structure and the equipment inside the facility, 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 completely fail (Carpenter, 1986).

2.2.2.7 Bioaerosols

Bioaerosol are defined as a collection of aerosolized biological particles that vary greatly in size, rating from 0.02 to 100 µm in diameter. Bioaerosols include airborne particles that are living, as well as other biologically active substances and volatile compounds that were released from living organisms. These may include bacteria, viruses, fungal spores, endotoxins, and other

microbial cells or fragments carried by the ventilation air or entrained from the animals, manure, ventilation ducts, and other surfaces that can support growth of microorganisms. Although most of these bioaerosols occur naturally in the environment in background concentrations, their numbers may be amplified in the animal environment to levels that may cause symptoms among immuno-compromised workers and animals burdened by the combined effects of other pollutant gases and particles (Predicala, 2003).

Studies of non-viable and viable particles in livestock buildings are cited giving 3 ranges, respectively, of 4 to 158 ($\times 10^6$) and 2 to 16 ($\times 10^6$) particles per m^3 . Spore counts range from 10^6 to 10^9 per m^3 in livestock buildings, spores being particularly associated with moldy hay and grain (Lacey, 1973).

2.2.3 Factors affecting air contaminant concentration

Indoor air quality can be influenced by many factors, such as air temperature, humidity, ventilation rate and type, type and amount of feed provided, type of feed delivery system, type of floors and litter used, and animal activity (Butera et al., 1991; Dawson, 1990; Heber and Stroik, 1987; Qi et al., 1992; Takai et al., 1998). In warm weather, high ventilation rates reduce airborne dust levels; in cold weather, however, low ventilation rates lead to high dust levels inside buildings (Carpenter and Mouldsley, 1986). Dust concentration depends also on air distribution, relative location to the dust sources, and occupants' activity levels in the building (Maghirang et al., 1994). Consequently, dust may not be distributed as uniformly within a ventilated airspace as gaseous pollutants. It is expected that there are spatial gradients of dust concentrations within a ventilated airspace (Wang, 2000). Hartung (1994) listed the potential of some factors to influence particulate concentrations in animal housing (Table 2-3).

Table 2-3 Factors that influence particulate concentrations in animal housing (Hartung, 1994).

Factors (if present or increased)	Particulate concentration *
Feeding-dry	+
Feeding-liquid	-
Activity of animals	+
Bedding	+
Stocking density	+
Air temperature	+
Relative humidity	-
Ventilation rate	-
Airspace per animal	-

* + increased - decreased

2.2.3.1 Facility design

Building design not only affects animal health and performance but also, directly or indirectly, the indoor air quality. The design of the ventilation system, ease of cleaning, access of animals to feed and water, space allowance, among others, can influence air contaminant concentration.

2.2.3.2 Manure handling and storage

Animal production introduces manure into the environment. High animal concentrations produce large volumes of manure. When manure dries it produces dust particles (Sweeten et al., 1988) that are high in endotoxin. Clinically, endotoxin (doses 20–300 µg) via the respiratory route in humans commonly induces tightness of the chest, airway irritation, and fever after 6–8 h. Less common symptoms are headache, joint and muscle pains, nausea, and fatigue (Rylander et al., 1989). Chest tightness, cough, dyspnea, and sputum production were reported after the inhalation of a 0.9 µg/ml endotoxin dose (Jagiello et al., 1996).

2.2.3.3 Methods of feeding

Type and method of feeding play a major role in the level of dust concentration inside livestock buildings. As mentioned in the previous sections, feed particles constitute the major portion of the airborne and settled dust particles.

2.2.3.4 Animal activity

Reduction in animal activity may help reduce the emission of dust particles. Researchers (Honey and McQuitty, 1979; Zhang, 1986; Takai, 1992) noted that the activity of pigs plays an important role in dust concentration in pig barns. Gordon (1963) noted that bedding and the level of swine activity had a significant effect on the viable aerosol production.

2.2.3.5 Ventilation

Ventilation plays a main role in sustaining the welfare and performance of confined livestock, by affecting thermal exchanges between the animal's body surface and the environment and by removing air pollutants (Sevi et al., 2002). Poor ventilation can lead to increased airborne particulate and gaseous pollutant concentrations (Rylander, 1986; Hartung, 1994). Poor ventilation is also responsible for increased airborne concentrations of viable microbes, NH₃ and CO₂, reduced feed efficiency, and enhanced aggressive interactions in cattle, in pigs, and in broiler chickens (Wathes et al., 1983; Massabie et al., 1997; Marrufo Villa et al., 1999; Spoolder et al., 2000).

2.2.3.6 Stocking density

Space allocation is known to affect both the performance and welfare of livestock. In addition, stocking density has been shown to affect directly the levels of gaseous pollutants and airborne particles in animal houses (Curtis, 1983).

2.2.3.7 Air temperature and ambient humidity

Van Wicklen and Albright (1987) found a relationship between outdoor air temperature and mean respirable aerosol concentration. They found that the mean daily respirable aerosol concentration increased significantly as the temperature decreased from 26.7 to 10.6 °C. Feddes et al. (1982) reported that dust concentration was found to be affected by temperature. Stroh et al. (1978) found that temperature had a minimum influence on the dust particle counts, but Heber and Martin (1988) reported that both the number and the net mass concentration of the total dust were negatively correlated to outside air temperature of the swine building. Takai (1992) found that a significant correlation existed between inside temperature and respirable dust concentration. Atia (1995) observed a negative correlation between outside temperature and dust concentration.

Heber and Martin (1988) found that both number and net mass concentration of total dust were negatively related to inside relative humidity. Takai (1992) found that there was a negative correlation between outside relative humidity and aerial dust concentration. Bundy (1974) found that dust removed by air ionization is not affected by relative humidity. High relative humidity enhances the survival of airborne pathogens (Harry, 1978; Donaldson, 1978). Christison (1988) specified that if relative humidity rises there will be an inevitable rise in concentration of air pollutants such as odorous gases and dust. There are two reasons suggested for the effect of RH on dust: (1) the absorption of water vapor by dust particles in humid air produce heavier particles which settle more rapidly, thus lowering aerial dust concentration (2) humid air increases the moisture content of the litter and settle dust, so that less dust becomes airborne (Atia, 1995). Increase in relative humidity will enhance agglomeration of particles with each other which will cause fast settling of particles due to the increase in its size (Smorodin et al., 1999). Hinds

(1999) mentioned that the increase in relative humidity will enhance the particle adhesion force to collection surfaces, which is given by the following empirical equation:

$$F_{adh} = 0.063d_p [1 + 0.009(\%RH)] \quad (2.1)$$

2.2.4 Summary of air contaminants

Air pollutants from livestock buildings include gaseous and particulate contaminants that are generated from the metabolic and physical activities of the animals - as well as from routine husbandry operations necessary to maintain the productivity and well-being of the animals. Exposure to these contaminants at excessive levels may pose nuisance and health concerns to animals, workers, and residents in the vicinity of livestock facilities. Dust is considered the most common and prevalent air contaminant in animal buildings. It originates from feeds, litter and fecal material of animals and can be of organic or inorganic origin. Factors that affect the concentration and distribution of air contaminants in livestock buildings include the design and use of the building, type and arrangement of feeding and bedding, waste handling and disposal, ventilation rate and air flow pattern, and animal activity.

2.3 Air Cleaning Methods in Livestock Buildings

Air quality in livestock buildings should be improved to prevent occupational health problems. Engineering control strategies include: (1) reducing emission or generation rates of the air contaminants (i.e., source control); (2) dilution and/or effective room air distribution (i.e., ventilation control); and (3) air cleaning (i.e., removal control). Source control strategies for dust include use of feed additives (fats or oils), cleaning of dusty surfaces, and spraying water or oil over dusty surfaces. Ventilation control includes purge ventilation and effective room-air distribution systems. Air cleaning strategies include use of gravitational settling chambers, air

filters, ionizers, or wet scrubbers. Dust reductions reported with these strategies have ranged from 15% for weekly washing of pigs and floors, to 23% with ionizers, to 76% with a rapeseed oil spray (CIGR, 1994).

2.3.1 Ventilation

A major method of controlling dust and air contaminants in enclosed livestock facilities is by mechanical ventilation (Atia, 1995). Ventilation can remove aerosol from livestock buildings especially during warm weather when the ventilation rates are high. During the winter, ventilation rates are reduced to conserve heat and to avoid chilling the animals. As ventilation rate decreases, the aerosol concentration in the enclosure increases (Bundy, 1974). Dust can be removed from air by ventilation, but normally sedimentation can play an important role in removing the dust (Carpenter and Fryer, 1990). Van Wicklen and Albright (1982) reported that incoming ventilation air contributes significantly to the number of particles and aerosols in the indoor environment. Sufficient air turbulence to suspend dust particles exist in most livestock buildings (Harry, 1978). Bundy (1984) showed that higher air velocities caused more inertial impaction of particles on building surfaces, thus helped remove dust from the air stream (Meyer and Manbeck, 1986).

2.3.2 Air misting

Misting of the incoming air wets the litter directly or indirectly as a result of high relative humidity (Atia, 1995). This will reduce airborne dust generation from the litter. Fogging is also used to reduce the generation of the dust in swine buildings (Nilsson, 1982). Water is used to reduce the amount of dust in swine buildings (Van't Klooster et al., 1993). Gian-Gupta et al. (1988) found that the ratio of dust particles smaller than 0.8 μm to total dust ranges from 10-

50%. The highest concentration of dust was in the particle size range of 3.2 μm , so the fogging system reduced the concentration of the larger dust particles, but not of smaller particles. Gustafsson (1994) reported that spraying small droplets of water into the air resulted in a significant reduction in dust concentration.

2.3.3 Gravitational settling chambers

All forms of respirable aerosol (viable and non viable) are subject to gravitational settling or sedimentation. Aerosol with diameter between 1 and 30 μm are governed by Stokes' law (Sheehy et al., 1967; Hemeon, 1955; Dwyer, 1966). Aerosols of diameter between 0.1 to 1 μm are governed by a modification of Stokes' law. A correction factor, Cunningham factor, is used when aerosol particle size reach the mean free path of air molecules.

A gravitational settling chamber may be used to remove particles greater than 50 μm in diameter. When using Stoke's law, the maximum air flow velocity that allows a particle of 10 μm in diameter to settle out is 0.003 m/sec. Therefore, most particles less than 10 μm in size will not settle out depending on the horizontal velocity and the size of the particle. Particles of diameters larger than 10 μm can settle out very quickly and are not considered to be in a harmful range for humans or livestock (Atia, 1995).

2.3.4 Fibrous filters

Fibrous filters are suitable for removing respirable aerosol from livestock facilities (Atia, 1995). They exist in different shapes and forms. Some units are capable of removing aerosols less than 1 μm (Van Wicklen and Albright, 1982). Removal efficiencies of fibrous filters vary. Some fibrous filters have removal efficiencies up to 99% (Veenhuizen, 1989). Van Wicklen and Albright (1982) recommended use of filters that have efficiencies of 95% or greater. Carpenter

and Fryer (1990) suggested that filters are good removal devices for dust in livestock barns. These filters are applicable to swine and dairy housing, but the cost of frequent cleaning and maintenance are very high because the filters are subject to rapid clogging in dusty environments. Hillman et al. (1992) found that air filtration was very effective in reducing the respiratory problems of calves.

2.3.5 Electrostatic precipitators

The use of air filters or electrostatic precipitators will aid viable aerosol reduction (Van Wicklen and Albright, 1982). Electrostatic precipitators are supplemental air cleaners which have an advantage of low pressure drop through the device and a high efficiency for respirable aerosols. Electrostatic precipitators have a high collection efficiency and low resistance to air flow (Hinds, 1999).

2.3.6 Wet scrubbers

Wet scrubbers are commonly used for the collection of particles and odors from air stream because of high collection efficiency and low cost. Different collection mechanisms (i.e., inertial collection, interception, and diffusion) affect the collection of particles. In addition to particle removal, wet scrubbing is a well known method to remove water soluble gases like NH_3 . Licht and Miner (1979) found that there was a highly significant relationship between odor removal and particle removal by scrubbers.

2.3.7 Electrostatic scrubbers

The removal of fine particles like dust, smoke, bacteria, spores or viruses, which are usually smaller than a few micrometers in diameter, still remains a great challenge for engineers. The efficiency of removal of fine particles by conventional methods rapidly decreases in the

submicrometer size range. Electrostatic scrubbers seem to address this problem and can effectively remove smoke, dust or microorganisms from the air (Balachandran et al., 2001).

The electrostatic augmentation of wet scrubbers was found to improve the collection of submicrometer particles (Pilat and Raemhild, 1979). In these scrubbers, electrical forces are introduced by imposing electrostatic charges onto the fine droplets before they enter the inlet of wet scrubbers. The force of mutual electrical attraction (Coulomb force) drives the particles toward the droplets. This contributes to the improvement of the overall collection efficiency of a scrubber with induced electrical charge on droplets and particles over conventional scrubbers. The charged droplets act as small spherical collecting electrodes sweeping the precipitation chamber. The particles are permanently captured by the drops as they are wetted by the scrubbing liquid (Balachandran et al., 2001).

The electrostatic scrubber removes most shortcomings of other techniques, which fail to effectively control the dust particles in the submicrometer size range. The charged droplet scrubbing substantially increases the overall collection efficiency as compared to the conventional inertial scrubbers. It also requires lower water consumption and lower pressure drop through the collecting chamber when operating at the same collection efficiency as the inertial scrubbers. In addition, the equipment utilizing electrostatic forces operates at lower relative velocities than that in which inertial collection is dominant (Jaworek et al., 1998). Both the droplet and the particle can also be charged to the same polarity. In that case, the repulsive forces drive the particle to the scrubber walls where they are washed out (Metzler et al., 1997).

The problem of removal of the charged dust by oppositely charged droplets was first considered theoretically by Kraemer and Johnstone (1955). They determined the collection efficiency, taking into account the Coulomb, image, and Stokes forces as well as the space

charge effect. Nielsen and Hill (1976a, b) calculated numerically the collection efficiency, taking into account the external electric field force and the electric dipole interaction force. The gravitational effects were considered by Beizaie and Tien (1980), and they concluded that the gravity is dominant when the dust particles flow collinearly with the gravitational force. Wang et al. (1986a, b) solved the problem of the dust deposition on a collector falling down and entrained by the flowing gas, but their solutions were restricted to two-dimensional geometry only, and the flow field was determined from approximate equations. Schmidt and Loffler (1992) solved the Navier – Stokes equations to determine the flow field near the collector, but these solutions were obtained for a fixed collector. Jaworek et al. (1997) studied the trajectories of the dust particles in the vicinity of a charged spherical collector from the differential equations of the particle motion and by determining the flow field near the collector from the numerical solution of the Navier – Stokes equations. Koyevnikova and Zimmels (2000) developed a more complex model using an array of stationary droplets and a single particle falling between them.

2.3.7.1 Charging mechanisms

There are many ways of charging particles (Moore, 1973; Cross, 1987); only three main charging mechanisms are applicable to liquids, i.e., corona charging (ionized field), contact (direct) charging, and induction charging. These methods can be illustrated by the nozzle and spray charger developed by Law (1978) as presented in Figure 2-1.

Figure 2-1 shows a continuous jet **J** of liquid issuing at a velocity **V** from a fluid nozzle **N** and directed towards an outlet end near which a sharply pointed discharge electrode **P** is located. By the interaction of high pressure air, the continuous liquid jet may be disrupted into discrete airborne droplets within a droplet-production zone **Z** between the nozzle **N** and the point **P**. Coaxial with this jet is a cylindrical electrode **C** that can influence the electric-field direction and

intensity in the zones **Z** and **P**. By appropriate connection of the conductors **L₁**, **L₂**, and **L₃** to various combinations of electrical potential, the three charging phenomena can be achieved (Xiao, 2000).

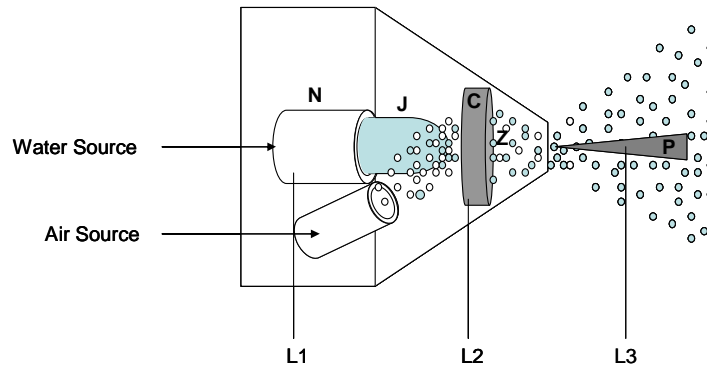


Figure 2-1 Schematic diagram of the electrostatic charging nozzle for water droplets (Law, 1978).

Corona (ionized field) charging. Grounding the conductors **L₁** and **L₂** and applying a sufficiently high D.C. potential to conductor **L₃** will result in the dielectric breakdown of the air immediately surrounding the metal point **P**. Consequently, for the cylindrical geometry shown in Figure 2-1, a self-sustaining gaseous-discharge current will flow between **P** and **C** such that the major portion of the cylindrical gap is occupied by unipolar air ions traveling outward along the radial electric-field lines to the non-ionizing electrode **C** (Law 1978). This method is described by a high voltage applied to a needle-point can create an intense electric field around it that is sufficient to ionize molecules of the surrounding air. A positively-charged conductor will repel the positive ions created, while the electrons that are released in the ionization process will be attracted to the conductor and neutralize some of its charge. With a negatively-charged conductor, the reverse is true and positive ions are attracted back to the conductor. The level of

charge is dependent upon the dielectric constant of the spray, its surface area, the electrical characteristics of the corona discharge, and the time within the ionized field.

When a stream of liquid passes near to the ionizing tip of the needle, the charged ions produced are attracted to the liquid and carried away by it. The needle is usually negatively charged, as higher voltages are required to create an equivalent positive corona. Liquids with a wide range of conductivities can be charged with this method (Arnold and Pye, 1980).

Contact (direct) charging. Charge transfer by conduction to the spray-liquid jet, and subsequently, to the generated droplets at their instant of formation, can be achieved if an excess supply of free charge is maintained on the metal nozzle itself by connection of conductor L_1 to a voltage source while L_2 and L_3 remain unconnected. For conductive liquids, maintenance of the fluid nozzle at an elevated voltage also necessitates having the entire bulk of the liquid and the liquid-handling system at that elevated voltage. While technically possible in certain industrial processes, system insulation and isolation problems generally preclude contact charging from having a wider application like agricultural applications (Law, 1978; Xiao, 2000).

Induction charging. If a positive potential is applied to the cylindrical electrode C in Figure 2-1 by connection of a voltage source between conductors L_1 and L_2 (L_3 remaining unconnected), then theoretically for any liquid having non-zero electrical conductivity an excess negative charge will accumulate on the grounded liquid jet J . This charge transfer results from the electrostatic induction of electrons onto the axial jet in order to maintain it at ground potential in the presence of the nearby charged cylindrical electrode. Individual droplets formed from this negatively charged continuous jet will depart with a net negative charge provided that the droplet-formation zone Z is subjected to the inducing electric field acting between the cylinder and the jet (Law, 1978).

If the electrode is negative, the reverse occurs and electrons repelled from the liquid to earth will provide a positively charged liquid. As the droplets are formed, the charge is retained on them. A conductive liquid is needed so that the charge transfers from earth to the liquid jet in the very short time while it passes the electrode. The level of charge induced per unit area of surface will be proportional to the voltage applied to the electrode.

The charge on the spray droplets is the opposite of that on the electrode, so some spray is liable to be attracted on to the electrode, which if wetted, is liable to short circuit the power supply. An air stream is used on some nozzles to blow droplets away from the electrode and keep it dry (Law, 1978).

2.3.7.2 Collection mechanisms

The collection of an aerosol particle by a charged droplet is the result of a number of simultaneous mechanisms of interaction between them, such as inertial impaction, direct interception, Brownian diffusion, and electrostatic, diffusio-phoretic, and thermophoretic forces (Nielsen and Hill, 1976b; Prem and Pilat, 1978). When an aerosol particle approaches a water droplet with a relative velocity, the particle may directly collide with the droplet (i.e., impaction), barely touch the droplet (i.e., interception), or entirely miss the droplet.

The relative effect of the mechanisms of interaction between the droplet and the particle depends upon the size of the particle. For particles with aerodynamic diameter greater than 2-3 μm , the dominant mechanisms of particle collection by droplets are impaction and interception. For particles smaller than 0.1 μm , Brownian diffusion becomes very important, and for particles between these two ranges, electrostatic deposition is the important collection mechanism.

A complete solution of the equation of motion for particles that includes all possible forces involved is extremely difficult to obtain (Xiao, 2000; Dhariwel et al., 1993). Many

investigators (Kraemer and Johnstone, 1955; Zebel, 1968; George and Poehlein, 1974; Nielsen and Hill, 1976a, 1976b; Prem and Pilat, 1978; Leong et al., 1983; Wang et al., 1986a, 1986b; Corbett, 1988; Fichman et al., 1990; Filippov, 1992) have simplified the equation of motion by neglecting forces that are small and considering only the dominant forces. Results of these studies showed that for small particles the effects of interception and inertial impaction are negligible. Theoretical results of George and Poehlien (1974), Corbett (1988), and Pully and Walters (1990) showed that collection due to interception alone depends on the parameter $s = r_p / r_d$. When $s \ll 1$, the effect of interception is negligible. Prem and Pilat (1978) showed that the effect of the inertial impaction is dominant over all other forces or all non-electrostatic forces for particles larger than 10 μm , and Leong et al. (1983) pointed out that the inertial effect was insignificant for 3- μm particles depositing on 30- μm falling water droplets. Collection due to inertial impaction depends on the Reynolds and Stokes numbers; for $\text{Stk} \ll 1$, the effect of inertial impaction is negligible. In the absence of external forces, Brownian diffusion is the dominant mechanism for the collection of small particles, and the single droplet collection efficiency due to all these mechanisms combined never exceeds 1.0. However, the single droplet collection efficiency due to Coulombic attraction when particles and collector are oppositely charged may reach values significantly greater than 1.0. Kraemer and Johnstone (1955) indicated that for certain conditions single droplet collection efficiencies as high as 3320 could be obtained.

2.3.8 Summary for air cleaning

Air quality in livestock buildings should be improved to prevent occupational health problems. Engineering control strategies include source control, ventilation control, and air cleaning. Source control strategies for dust include use of feed additives (fats or oils), cleaning

of dusty surfaces, and spraying water or oil over dusty surfaces. Ventilation control includes higher ventilation rate and effective room-air distribution systems. Air cleaning strategies include use of air filters, ionizers, or wet scrubbers. A potential dust-reduction method is spraying charged water into the airspace. The principles of charging and collection mechanisms are described.

2.4 Measurement of Electrostatic Charge

Electrostatic charging of particles is an important phenomenon that is used in many applications (Matsusaka and Masuda, 2003), including electrophotography (Schein, 1992; 1999), dry powder coating (Bailey, 1998), electrostatic precipitator (Lloyd, 1998), separation of powder (Gupta et al., 1993; Yanar and Kwetkus, 1995), electromechanical particulate operation (Ghadiri et al., 1992; Balachandran et al., 1997), powder flow measurement (Ghadiri et al., 1992; Balachandran et al., 1997; O'Neill and Willis, 1987; Masuda et al., 1994; Masuda et al., 1998), and tomography (Machida and Scarlett, 1998; Gajewski, 1996). These applications require an understanding of electrostatic charge and particle charging. In some cases, electrostatic charge is considered as a nuisance (Joseph and Klinzing, 1983; Nifuku et al, 1989; Adhiwidjaja et al., 1999) and source of explosion hazards (Jones and King, 1991).

Electrostatic charge can be beneficial as in the control of dust by the use of electrically charged filters or precipitators, or it may be a drawback, by causing errors during sampling. Similarly, its effects on pulmonary deposition may make it useful in medication or a complication so far as hazardous dust is concerned (Brown, 1997). Studies done by Hoenig (1977) and Gillespie (1955) have shown that most industrial pollutants and naturally occurring dust particles acquire electric charges as they are dispersed into the air. Walkenhorst (1971),

Hoening (1977), and Hassler and Birgitta (1978) have also shown that the polarity and magnitude of the charges on these particles depend upon their size and origin (coal, soil, mineral, etc.).

Many factors can influence electrostatic charging and measurement of electrostatic charge: quantity and physical properties of the material, chemical composition, and moisture equilibrium state (ASTM, 2004). Brown (1997) stated that the three most important parameters governing the behavior of aerosol particles are their size, electric charge, and shape, and concluded that the simultaneous measurement of size and charge is necessary if the properties of particles are to be understood and their behavior controlled.

2.4.1 Electrostatic charge

The SI unit of charge is coulomb, which is defined as:

$$1 \text{ Coulomb} = 1 \text{ Ampere} \times 1 \text{ second} \quad (2.2)$$

Electric charge is either positive or negative. The natural elemental unit of negative electric charge is that possessed by an electron. In terms of fundamental physical constants, the coulomb is measured in units of the elementary charge e :

$$1 e = -1.60217733 \times 10^{-19} \text{ Coulomb} \quad (2.3)$$

A neutral, or normal, atom consists of one or more orbital electrons (negatively charged) and a much heavier nucleus of equal positive charge. The total, or net, charge of the normal atom is zero. If one or more orbital electrons is removed, the atom is ionized (Kraus, 1953).

2.4.2 Faraday cage sampler

A Faraday cup or cage is used to measure the charge carried by stationary or moving materials: a typical Faraday cup is a cylindrical, shielded container into which the charged body is slowly placed, and the charge induced on the inner electrode of the cup is determined by an electrometer (Kucerovsky and Kucerovsky, 2003). As stated in ASTM Standard D4470 (ASTM,

2004): “The Faraday cage consists of two conducting enclosures, one enclosed and insulated from the other. The inner enclosure is electrically connected to the shunt capacitors and the electrometer input. It is insulated from the outer enclosure by rigid, very high resistance, insulators which have resistance practically independent of relative humidity (an example is polytetrafluoroethylene or PTFE). The inner enclosure should be of such construction that the test specimen can be substantially surrounded by it. The outer enclosure is connected to ground and surface to shield the inner enclosure from external fields which could affect the measurement.”

In measuring the charge of particles or objects, Brown (1997) stated that it is not necessary for the particles or a charged object actually to give up their charge. It is sufficient for them to be contained in a Faraday cage and to induce an equal charge. The cage will register the approach of the charged particles before contact occurs, because of the charge induced (Fewkes and Yarwood, 1956), and induction can be used to measure the charge, even if contact never takes place. As such, airborne charged particles can be made to pass through a partial Faraday cage in the form of a conducting ring and induce a charge that can be sensed by an electrometer. However, only a complete Faraday cage will develop an induced charge equal to that of the charge contained (Brown, 1997).

The net charge on an aerosol can be measured by collecting it in a Faraday cup. By dividing the collected charge by the number of particles sampled, the average particle charge can be obtained. The mass of collected particles can also be measured and then used to determine the net charge-to-mass ratio of collected particles. Penney and Lynch (1957) collected particles on a filter surrounded by a Faraday cage, and made estimates of the total mass of aerosol by

weighing the filter. John (1980) developed a Faraday cup that involved pumping the aerosol through a high-efficiency filter surrounded by a metal can insulated from ground.

2.4.3 Other methods to measure the charge on droplets

Other methods have been developed to measure the charge of particles. These include the Millikan method and laser Doppler anemometry. In the Millikan method, the charge on an individual particle is measured by observing the way in which it moves under the influence of gravity and an electric field (Xiao, 2000). The technique was developed by Millikan, who used an electric field opposing gravity for the determination of the charge on an electron. A charged particle is introduced into the space between two horizontal plane electrodes and its motion observed using a telescope or long focal length microscope.

The laser Doppler velocimeter measures the velocity of particles without disturbing the electric field or the particle motion. It can be used to measure the velocity of a particle in an electric field, to obtain the mobility. Laser Doppler systems were originally designed to measure fluid flows and to detect the distribution of the velocities in a cloud of particle. The instrument normally integrates the signal from a large number of particles, building up a velocity distribution over a timescale which is much longer than the timescale of fluctuations in the flow. However, it is also possible to measure the velocity of individual particles (Sato, 1980; Ross, 1981).

2.4.4 Summary for electrostatic charge

Electrostatic charge of particles is important because most industrial pollutants and naturally occurring dust particles acquire electric charges as they are dispersed into the air. The behavior of aerosol particles is affected by their size, shape, and electric charge; as such, simultaneous measurement of size and charge is necessary if the properties of particles are to be

understood and their behavior controlled. Faraday cups are used to measure the charge carried by stationary or moving materials: a typical faraday cup is a cylindrical, shielded container into which the charged body is slowly placed, and the charge induced on the inner electrode of the cup is determined by an electrometer.

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CHAPTER 3 - MEASUREMENT OF THE ELECTROSTATIC CHARGE OF AEROSOL PARTICLES

3.1 Abstract

A dynamic Faraday-cup sampler was developed for measuring the net charge-to-mass ratio of aerosol particles. The device involves collecting particles on a filter and measuring the electrostatic charge induced on the filter. Calibration tests by using electrostatic charge of known magnitude and polarity showed that the device has a good sensitivity and stability. The sampler was used to measure the electrostatic charge of various types of airborne particles, including corn starch, sodium bicarbonate (NaHCO_3), positively-charged water spray, negatively-charged water spray, and uncharged water spray. The net charge-to-mass ratios were -0.11 (SD=0.07) mC/kg for corn starch, +0.20 (0.001) mC/kg for NaHCO_3 , +7.24 (1.6) mC/kg for the positively-charged water spray, -6.47 (0.9) mC/kg for the negatively-charged water spray, and -0.30 (0.12) mC/kg for the uncharged water spray. The device was also used to measure the charge of airborne dust in a swine building; the mean net charge-to-mass ratio was +0.68 (0.31) mC/kg.

3.2 Introduction

Electrostatic charging of particles is an important phenomenon that involves many applications (Matsusaka and Masuda, 2003), including electrophotography (Schein, 1992; 1999), dry powder coating (Hughes, 1984; Bailey, 1998; Kleber and Makin, 1988), electrostatic precipitation (Lloyd, 1998), separation of powder (Gupta et al., 1993; Yanar and Kwetkus,

1995), electromechanical particulate operation (Ghadiri et al., 1992; Balachandran et al., 1997), powder flow measurement (Ghadiri et al., 1992; Balachandran et al., 1997; O'Neill and Willis, 1987; Masuda et al., 1994; Masuda et al., 1998), and tomography (Machida and Scarlet, 1998; Gajewski, 1996). These applications require a good understanding of electrostatic charge and particle charging.

In some cases, electrostatic charge is considered a nuisance (Joseph and Klinzing, 1983; Nifuku et al., 1989; Adhiwidjaja et al., 1999), can cause dust explosion hazards (Jones and King, 1991), and can cause errors during aerosol sampling. In other cases, electrostatic charge can be beneficial as in the control of dust by the use of electrically charged filters or precipitators. Similarly, charge effects on pulmonary deposition may make it useful in medication or a complication so far as hazardous dust is concerned (Brown, 1997).

Many factors can influence electrostatic charging and measurement of electrostatic charge: quantity, physical characteristics of the material, chemical composition, and moisture equilibrium state (ASTM, 2004). Hoenig (1977) and Gillespie (1955) have shown that most industrial pollutants and naturally occurring dust particles acquire electrostatic charges as they are dispersed into the air. Walkenhorst (1971), Schutz (1967), Hoenig (1977), and Hassler and Birgitta (1978) have also shown that the polarity and magnitude of the charges on these particles depend upon their size and origin (e.g., coal, soil, and mineral).

Brown (1997) stated that the three most important parameters governing the behavior of aerosol particles are their size, electric charge, and shape. He concluded that simultaneous measurement of size and charge is necessary if the properties of particles are to be understood and their behavior controlled.

Several methods are available to measure the charge of airborne particles; however, majority of these are sophisticated, expensive and designed primarily for laboratory or stationary use. The Faraday cup is a popular, versatile and often a key device, used for measuring electrostatic charge. John (1980) developed a Faraday cup sampler to measure the charge carried by stationary or moving materials. A typical Faraday cup is a cylindrical, shielded container into which the charged body is slowly placed, and the charge induced on the inner electrode of the cup is determined by an electrometer (Kucerovsky and Kucerovsky, 2003). Brown (1997) stated that it is not necessary for a particle to give up its charge; it is sufficient for it to be contained in a Faraday cage and to induce an equal charge.

This study was conducted to develop a reliable and portable device for measuring the amount and type of charge carried by the aerosol particles. Specific objectives were to:

1. Develop a device for measuring the net charge-to-mass ratio of particles based on the ASTM standard;
2. Use the device to measure the net charge-to-mass ratio of dispersed particles (solid and liquid); and
3. Characterize the electrostatic charge of dust particles in a swine building.

3.3 Development of the Dynamic Faraday-cup Sampler (DFCS)

3.3.1 Description of the sampler

A dynamic Faraday-cup sampler or DFCS (Figs. 3-1 and 3-2) was developed in accordance with ASTM Standard D4470-97 (ASTM, 2004) and based on the design by John (1980) and Hinds and Kennedy (2000). It consists of two conducting enclosures, one enclosed and insulated from the other. The inner enclosure has two small openings for air inlet and outlet;

the openings are kept small to reduce leakage of external field into the cup. It is electrically connected to the electrometer input and has a dust collection filter with a back-up metal screen. It is insulated from the outer enclosure by a rigid, high resistance insulator (polytetrafluoroethylene or PTFE). The outer enclosure is connected to a grounded base and serves as a shield for the inner enclosure from the external fields that could affect the measurement. The Faraday cup has a minimum resistance to ground of 10^8 ohms to reduce charge leakage to ground.

The sampler is connected to a low-volume sampling pump that draws air and particles into the device and collects the particles onto the filter (type AE, SKC, Eighty Four, PA). The mass of particles collected on the filter is measured by weighing the filter before and after sampling in an electronic microbalance (Model AG245, Mettler-Toledo, Hightstown, NJ) with a sensitivity of 0.01 mg. The device is electrically connected to an electrometer (Model 6514, Keithley Instruments, Inc., Cleveland, OH), which is controlled by a computer. The electrometer has a very high sensitivity of the order of 10^{-15} A and high input impedance. The data from the electrometer are collected and managed by ExceLINX[®] software (Keithley Instruments, Inc., Cleveland, OH).

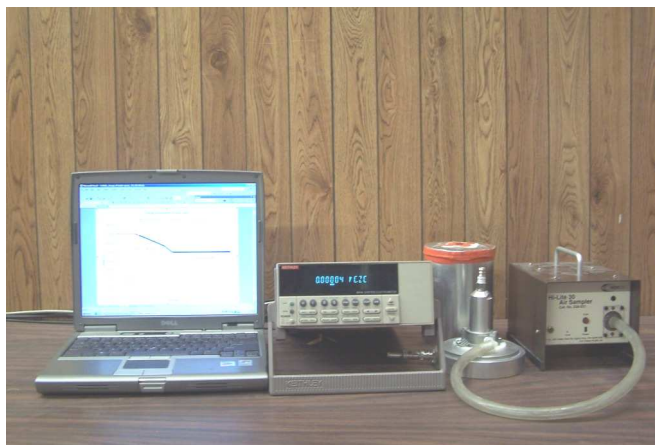


Figure 3-1 Photograph of the dynamic Faraday-cup sampler (DFCS) components.

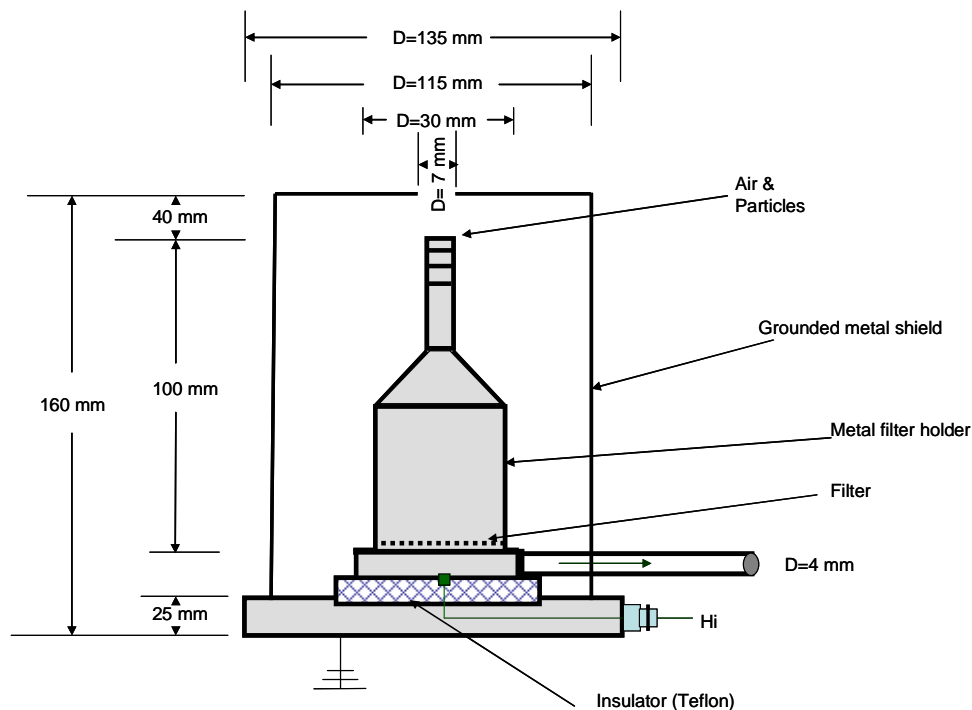


Figure 3-2 Schematic diagram of the dynamic Faraday-cup sampler (DFCS) for measuring the net charge-to-mass ratio of airborne particles.

3.3.2 Principle of operation

The principle of operation of the DFCS is based on Gauss's law. To illustrate, consider a certain charge Q with an electric field E and electric flux density D that is situated at the center of an imaginary spherical shell of radius r , and the medium is air (ϵ_0 , permittivity of air = 8.85×10^{-12} F/m) (Fig. 3-3). For a material with electrical permittivity ϵ , the electrical field quantities D and E are related by (Ulaby, 2004; Kraus and Fleisch, 1999):

$$D = \epsilon E \quad (3.1)$$

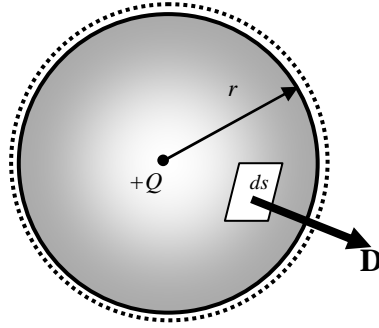


Figure 3-3 Electric flux \mathbf{D} due to point charge Q in the center of an imaginary spherical shell of radius r .

Applying Gauss's law to a spherical shell (radius r , and surface area s) just outside the shell, the charge is given by:

$$Q = \oint_S \mathbf{D} \cdot d\mathbf{s} \quad (3.2)$$

Combining equations 3.1 and 3.2,

$$Q = \epsilon_o \oint_S \mathbf{E} \cdot d\mathbf{s} = 4\pi r^2 \epsilon_o E \quad (3.3)$$

Another analysis presented by Kraus (1953) and Ramirez (2005) stated that if a charged object is introduced into a closed metallic recipient, the charges on the walls of the closed metallic recipient will become polarized. The internal wall of the cup will be polarized with the charge opposite to the polarity of the object and the external surface of the cup will take the same charge polarity as that of the object. In practical applications, the closed metallic recipient is open in one extreme to allow the charged object to enter. Certain specifications about how deep the charged object should be inside the cup make the results equal as if the container were totally closed. It is important to note that the charged object does not need to be in contact with the

internal walls of the cup in order to measure the charge.

Mathematically, this principle was presented by Kraus (1953) as follows: Let a point charge $+Q$ be placed at the center of the shell (Fig. 3-4). The point charge has a radial electric field, E_a .

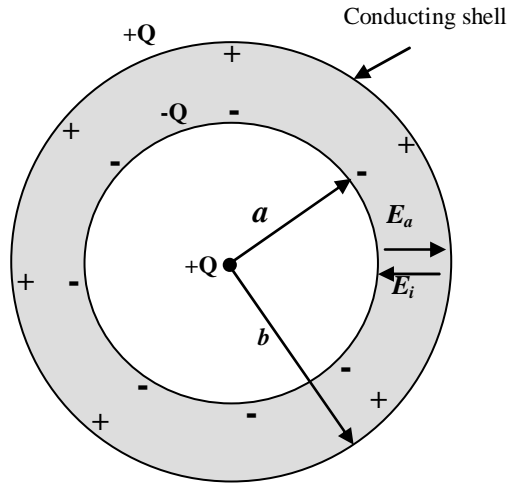


Figure 3-4 Conducting shell of wall thickness $(b - a)$ with point charge $+Q$ at center.

The total field E in the conducting wall should be zero, which requires an induced field E_i inside the wall such that

$$E_a + E_i = E = 0 \quad (3.4)$$

or

$$E_i = -E_a \quad (3.5)$$

The induced field E_i is produced by a distribution of induced negative charges on the inner shell wall and induced positive charges on the outer shell wall as indicated in Figure 3-4. The charge $+Q$ at the center of the shell induces an exactly equal but negative charge ($-Q$) on the inner surface of the shell, and this in turn results in an equal positive charge ($+Q$) distributed over the outer surface of the shell.

Likewise, consider the DFCS in which the charge of particles that are collected on the filter and that of the particles that are traveling from the inlet to the filter will transfer to the outer surface of the inner enclosure (filter holder) (Fig. 3-5). In this case the net charge will continuously increase as the particles accumulate on the filter. After the charge is transferred to the outer surface of the inner enclosure, it could be measured by measuring the electric field \vec{E}_O generated by this charge. The commonly used method to measure the electric field \vec{E}_O is by measuring the voltage V between the inner electrode (filter holder) and outer electrode (shield). Therefore, in order to determine the charge Q the following equation will be used:

$$Q = cV \quad (3.6)$$

If the device is connected to an electrometer:

$$c = c_c + c_l + c_e \quad (3.7)$$

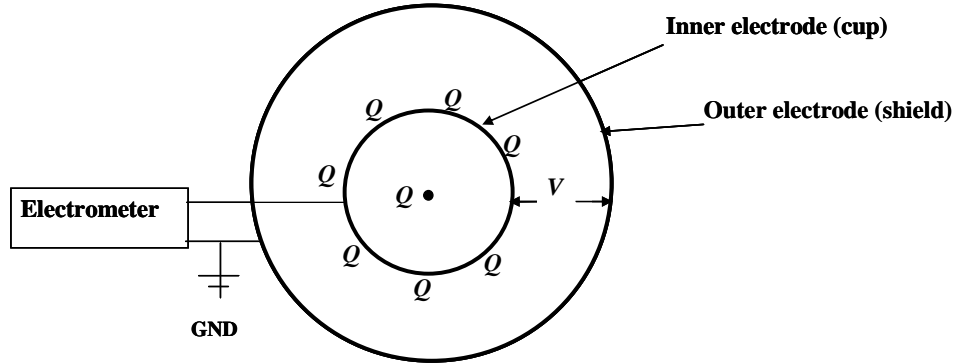


Figure 3-5 Setup of charge measurement using the faraday cage sampler.

3.3.3 Calibration

The accuracy of the DFCS was first checked by using electrostatic charge of known magnitude and polarity. A calibration circuit (Fig. 3-6) was prepared and used to generate known charges. The calibration circuit components consisted of the following parts: (1) variable

DC voltage power supply (Bk Precision Triple, MaxTec Instrumental Corp., Chicago, IL) that generated three fixed voltage values (1, 2, 3 VDC); (2) three different capacitors (0.1, 0.01, 0.001 μF); and (3) electrometer. Different charges were obtained by changing the combination of voltage and capacitor. The generated charge was first measured directly by the electrometer then by the DFCS. Figure 3-7 shows the relation between the measured charge and calculated charge. The % error ranged from 0.2 to 8.3%. Sources of errors include the cup itself, connecting lines, electrometer, and capacitors used in the calibration circuit.

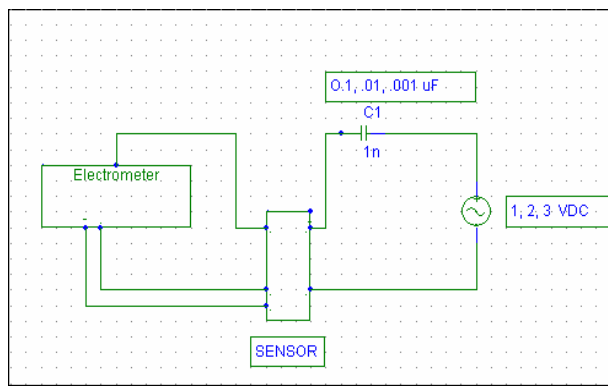


Figure 3-6 Schematic diagram showing the circuit components for generating a specified charge.

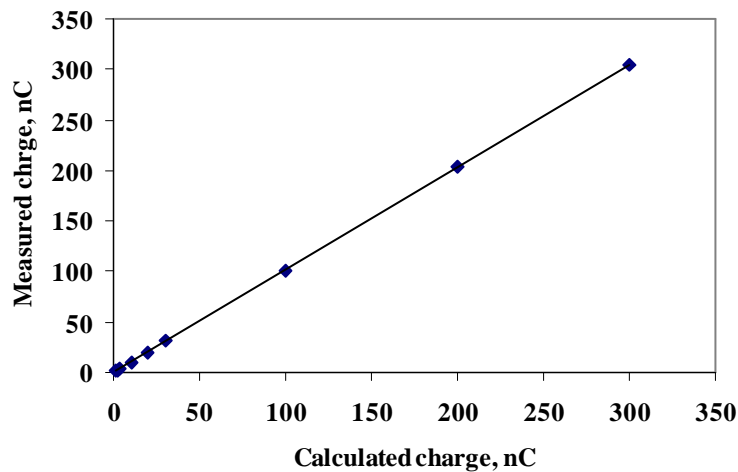


Figure 3-7 Measurement of charge via the charge measurement device vs. calculated charge.

3.4 Charge Measurement

3.4.1 Description of the measurements

The DFCS was used to measure the net charge-to-mass ratio of selected particles. Three sets of experiments were conducted: (1) dispersed solid particles in an enclosed experimental chamber; (2) water spray in the same enclosed experimental chamber; and (3) airborne particles in a swine building.

The first set of experiments involved dispersion of solid particles in an experimental chamber and measurement of the charge of the airborne particles. Two types of powders were considered: corn starch and fire extinguisher grade sodium bicarbonate (NaHCO_3) (Table 3-1). These particles were selected based on safety and size distribution. They were also used as test particles in Chapter 5. The particle densities, as measured with a multipycnometer (Quantachrome Instruments, Boynton Beach, FL), were 1.53 g/cm^3 (standard deviation, $\text{SD}=0.06 \text{ g/cm}^3$) and 2.22 g/cm^3 ($\text{SD}=0.02 \text{ g/cm}^3$) for corn starch and NaHCO_3 , respectively.

Table 3-1 Powder amount deployed, water amount sprayed, and number of replicates.

Particle	Mass deployed (g)	SD	No. of replicates
Corn starch	10.74	0.66	4
NaHCO_3	5.9	1.43	3
Uncharged water spray	480	-	2
Negatively-charged water spray	480	-	5
Positively-charged water spray	480	-	3

All experiments were conducted in an enclosed experimental chamber ($L=3.6 \text{ m}$, $W=2.4 \text{ m}$, $H=2.4 \text{ m}$) (Fig. 3-8). The air temperature and relative humidity were maintained at 25°C and 40%, respectively. The experiments involved the following general procedures:

1. The experimental chamber was prepared by cleaning the surfaces and running its air filtration system. The ventilation and air filtration systems were not operated during the experiment, so that air exchange in the room was primarily through natural infiltration/exfiltration.
2. A pre-conditioned sampling filter was weighed and installed onto the DFCS. The DFCS was set up near the center of the chamber and then was operated for 1 min prior to dispersion of the particles to measure the background charge. The sampling pump was not operated.

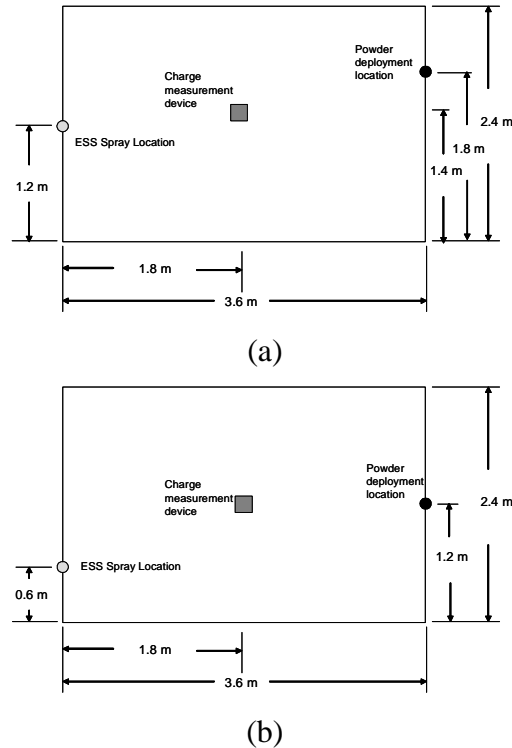


Figure 3-8 Schematic diagram of the experimental chamber and setup: (a) elevation and (b) plan view).

3. Particles were introduced into the chamber by using a pressurized canister with aluminum nozzle at 80 psig. A nominal mass of 20 g was used; the actual mass deployed ranged

from 7.4 to 12.5 g for corn starch and from 2.7 to 8.3 g for NaHCO_3 . Dispersion took approximately 2 sec. To further disperse the particles inside the chamber, two mixing fans inside the chamber were operated for about 1 min.

4. The DFCS, including the pump, was operated for about 2 min to collect particles onto the filter and also to measure the charge induced on the filter.
5. The sampling filter was weighed after the measurement to obtain the mass of collected particles.

The second set of experiments considered uncharged and charged (negatively charged and positively charged) water sprays. The charged water spray was generated using an electrostatic spraying system (Electrostatic Spraying Systems, Inc., Watkinsville, GA). The spraying system was operated for 4 min at a liquid flowrate of approximately 120 mL/min (water tank pressure of 15 psig) and droplet size of 21 μm . The procedure used for solid particles was followed.

In the third set, the DFCS was used to measure the net charge-to-mass ratio of airborne particles in a swine finishing barn at the Kansas State University Swine Teaching and Research Unit (Manhattan, KS). Measurements were done during the months of October and November, 2006, the sampling location was near the center of the building. The barn was mechanically ventilated. During sampling the barn was occupied by 160 hogs. Table 3-2 summarizes the environmental conditions during the sampling.

Table 3-2 Measured parameters inside the swine building during the sampling period.

Parameter	Mean Value
Dust mass concentration (mg/m ³)	0.89
Air temperature (°C)	24.5
Relative humidity %	53.5
Geometric mean diameter of the airborne particles based on mass (µm)	9.34
Geometric standard deviation of the airborne particles based on mass	2.11
Geometric mean diameter of the airborne particles based on number (µm)	0.89
Geometric standard deviation of the airborne particles based on number	1.81

For all cases, the net charge-to-mass ratio (mC/kg) was calculated using the following equation:

$$q_N = \frac{q - q_b}{mass_{filter}} \quad (3.13)$$

where q_N is the net charge-to-mass ratio, q is the net charge measured by the electrometer, q_b is device background charge, and $mass_{filter}$ is the mass of particles collected on the filter.

3.4.2 Net charge-to-mass ratio

Figure 3-9 shows a typical plot of the measured charge. Before the sampling pump was turned on, the background charge (i.e., charge caused by the capacitance of the system components) was first measured for about 20 s. When the sampling pump was turned on, the measured charge started to increase due to the accumulation of particles on the collection filter and the transfer of the particle charge to the device electrode. When the pump was turned off, the charge stabilized, and at this point the measured charge was used to calculate q_N of the collected particles.

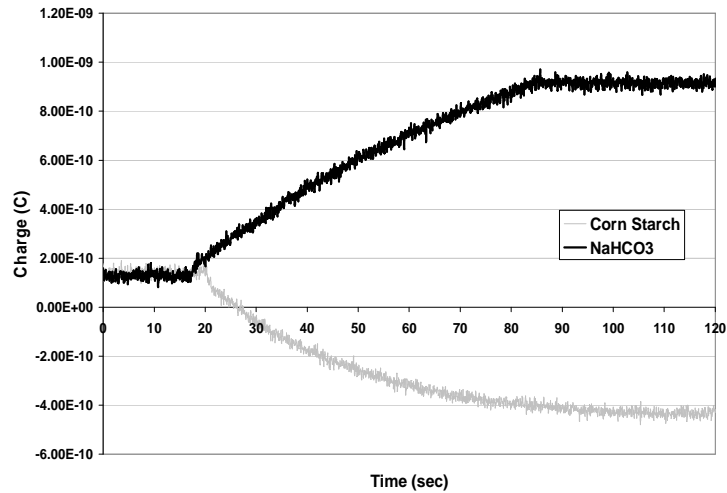


Figure 3-9 Charge of NaHCO₃ and corn starch measured by the DFCS.

Table 3-3 summarizes the mean values of q_N for the dispersed corn starch and NaHCO₃. Corn starch had a slightly negative q_N ; NaHCO₃, on the other hand, had a slightly positive q_N . The source of charge on the dispersed particles is mainly due to triboelectrification (i.e., the process of charging two dissimilar bodies by contact and/or rubbing), caused by the friction between the dispersed particles with the canister aluminum nozzle, and the friction between particles with each other. The type of materials in contact will determine the polarity and the condition and energy of contact will determine the magnitude. There are many factors that affect triboelectrification of materials such as environmental factors, including humidity and pressure, or material characteristics, including the type of material, surface roughness, and contamination. Other factors may relate to the contact like force of contact and type of movement during contact.

Table 3-3 also shows the mean values of q_N for the water droplets. The “uncharged” water spray had a slightly negative q_N . With induction charging, large values of q_N were

achieved (i.e., -6.47 mC/kg for the negatively-charged water spray and +7.24 mC/kg for the positively-charged water spray).

Table 3-3 Mean net charge-to-mass ratios of aerosolized particles, as measured with the dynamic Faraday-cup sampler.

Material	Net charge-to-mass ratio (mC/kg)	
	Mean	Standard Deviation
Corn starch	-0.11	0.07
NaHCO ₃	+0.20	0.001
Uncharged water spray	-0.30	0.12
Negatively charged water spray	-6.47	0.9
Positively charged water spray	+7.24	1.6
Swine dust	+0.68	0.31

Inside the swine building, the mean q_N of airborne particles was +0.68 (SD=0.31) mC/kg. The magnitude of charge of the airborne particles in livestock buildings is likely affected by many variables such as environmental conditions (i.e., temperature, humidity) and activities inside the buildings (e.g., feeding). The measured q_N value of aerosol particles in livestock building was higher than those for corn starch and NaHCO₃, possibly due to the nature of the particles in addition to the environmental conditions inside the livestock building.

Knowledge of the electrostatic charge of airborne particles is essential to designing effective air cleaning devices. In this research, the magnitude and polarity of aerosol particles

and water droplets that were used to remove those particles is very important to achieve the maximum removal efficiency.

3.5 Conclusions

This research developed a portable device for measuring the net charge-to-mass ratio of airborne particles. The following conclusions were drawn from this research:

- The device can be used to measure the net charge-to-mass ratio of solid particles and liquid droplets. Calibration by using known charge showed % error ranging from <1% to 8.3%.
- The electrostatic charge of particles is affected by the type of particle and the charging method. The mean values and standard deviations of the net charge-to-mass ratio for corn starch, NaHCO₃, positively-charged water spray, negatively-charged water spray, and uncharged water spray were -0.11 (SD=0.07), +0.20 (0.001), +7.24 (1.6), -6.47 (0.9), and -0.30 (0.12) mC/kg, respectively.
- The net charge-to-mass ratio of airborne particles in a swine building was +0.68 mC/kg. The charge seems to be affected by environmental conditions and the activities inside the buildings.

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CHAPTER 4 - CHARACTERIZATION OF DUST IN A MECHANICALLY VENTILATED LIVESTOCK BUILDING

4.1 Abstract

The concentration, particle size distribution, electrostatic charge, and true density of particles in a swine finishing building were measured. These parameters are necessary for the remainder of the research. Results showed mean dust concentration of 0.89 (SD=0.45) mg/m³, geometric mean diameter of particles of 9.34 μm, and geometric standard deviation of 2.11. The mean net charge-to-mass ratio was +0.68 mC/kg with SD = 0.31 mC/kg. The true density for swine house dust and swine feed were 1.84 g/cm³ (SD = 0.03) and 1.53 g/cm³ with (SD = 0.05), respectively.

4.2 Introduction

The air in livestock buildings contains a large number of pollutants that can be both harmful and aggravating. The most prominent air pollutants are odors, gases, dust, microorganisms, and endotoxins (Hartung et al., 1998). They are widely considered to be the principal risk factors for respiratory diseases (Clark et al., 1983; Donham et al., 1986; Wathes and Randall, 1989). There is epidemiological evidence that the health of farmers working in animal houses may be harmed by regular exposure to these air pollutants (Donham, 1987; Whyte et al., 1993). In broilers, about 30% of the birds that were rejected at meat inspection showed lung lesions (Valentin et al., 1988). Particulate emissions such as dust and microorganisms from buildings can play a role in respiratory problems in people living in the vicinity of animal enterprises. Muller and Wieser (1987) calculated the travel distance of viable bacteria from a

laying hen house to be 200 to 300 m downwind. Table 4-1 lists the suggested threshold limit values for indoor air contaminants in swine buildings.

Table 4-1 Suggested threshold limit values for indoor air contaminants in swine buildings.

Air contaminant	Humans	Animals	Reference
Inhalable dust, mg/m ³	2.40	3.70	Donham and Cumro, 1999
	-	3.40	Wathes, 1994
Respirable dust, mg/m ³	0.23	0.23	Donham and Cumro, 1999
	-	1.70	Wathes, 1994
Total endotoxin, EU*/m ³	614	1540	Donham and Cumro, 1999
Respirable endotoxin, EU/m ³	0.35	-	

The dust from livestock buildings contains a variety of compounds that are potentially hazardous agents (Donham, 1993). Table 4-2 summarizes the compounds that have been found in animal house dust. There are allergic agents, infectious microorganisms, enzymes, and toxic gases. For most of these compounds, it is not clear what their impacts are; combined effects of several compounds are usually suggested (Hartung et al., 1998).

Dust concentration inside animal buildings varies based on the type of animal, the building, and environmental characteristics. Table 4-3 shows dust concentrations levels that have been measured in different animal buildings.

This work was conducted to characterize the dust in a swine finishing building. The mass concentration, number concentration, particle size distribution, electrostatic charge, and true density of the particles were measured. These parameters are necessary for the remainder of the research.

Table 4-2 Compounds found in bioaerosols of livestock housing (Hartung et al., 1998; Donham, 1993).

Bioaerosol components
Feed particles (grain dust, antibiotics, growth promotors)
Swine proteins (urine, dander, scrum)
Feces (gut, gut epithelium, microbial flora, undigested feed)
Mold
Pollen
Grain mites, insect parts, Gram-negative bacteria
Endotoxin
Mesophilic bacteria
Actinomycetes
Virus
β 3-1,3-glucan
Microbial proteases
Mycotoxin
Ammonia and other gases, adsorbed to particles
Pathogens
Ultrafine dust
Plasmids
Fiber
Mineral ash
Pharmaceuticals

Table 4-3 Measured dust concentrations in the air of livestock buildings.

Animal Species	Respirable Dust, mg/m ³	Inhalable Dust mg/m ³		Source	
		Mechanical Ventilation	Natural Ventilation		
Beef	0.04 – 0.09	0.15 – 1.01		Hartung et al. 1998; Takai et al., 1998	
Calves	0.03 – 0.08	0.26 – 0.33			
Cows	0.03 – 0.17	0.10 – 1.22			
Broilers	0.42 – 1.14	3.83 – 10.40			
Laying hens	0.03 – 1.26	0.75 – 8.78			
Fattening pigs	0.10 – 0.29	1.21 – 2.67			
Sows	0.09 – 0.46	0.63 – 3.49			
Piglets	0.15 – 0.43	2.80 – 5.50			
Swine	0.01 – 0.22	0.12-2.14	-		Maghirang et al.,1997
	0.10 – 0.11	2.13	2.19		Predicala et al., 2001
		6.90	8.1 – 15	Heber and Stroik, 1988	
		3.20	5.20	Donham et al., 1986	
		1.30	2.70	Meyer and Manbeck, 1986	
		6.40	9.60	Curtis et al., 1975	

4.3 Materials and Methods

4.3.1 Description of the test building

Field measurements were conducted at the swine finishing barn at the Swine Teaching and Research Unit, Kansas State University, Manhattan, KS. The mechanically ventilated barn has dimensions of 34 m long, 12 m wide, and 2.5 m high (Figs. 4-1 to 4-4). The building structure consists of two main parts: (1) the base part that contains the building foundation, solid and slatted floor, and pens; and (2) the upper part consisting of a metal structure that made the

body of the building and the walls of the buildings (i.e., outer metal surface and polished PVC panel for the inner surface with thermal insulation between them in addition to framing).



Figure 4-1 Exterior of the barn showing the air inlets and ventilation fans.

There are two double-rows of animal pens, with alleys located centrally and along each wall, and containing a total of 80 pens arranged in four rows. Each pen (1.6 m × 1.6 m) has a feeder and drinker and, at the time of measurements, each pen had two animals for a total of 160 animals.

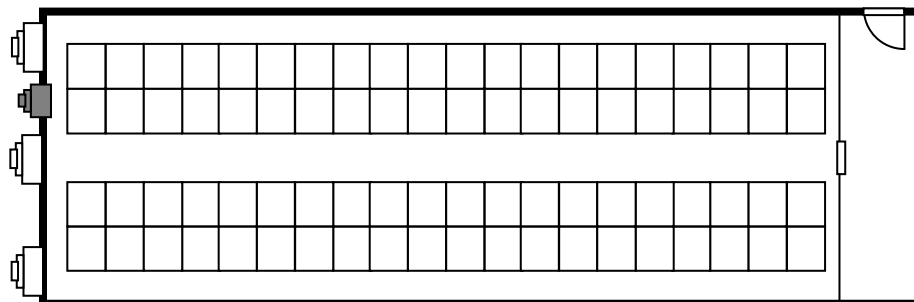


Figure 4-2 Schematic diagram of the barn showing the distribution of the 80 pens inside the building (plan view).

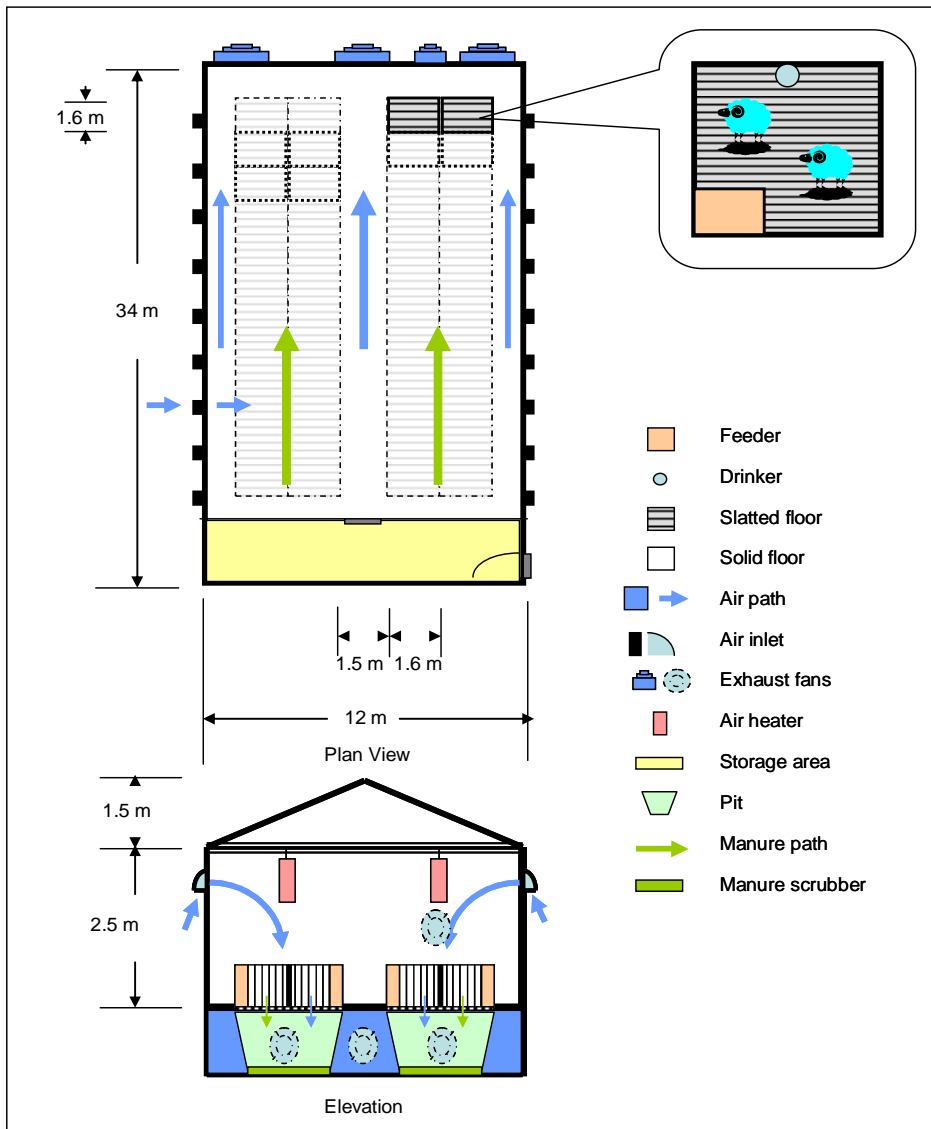


Figure 4-3 Schematic diagram of the barn.



Figure 4-4 Photograph showing the interior of the barn.

The barn has a slotted floor for the pens and solid floor for the alleys (Fig. 4-5). The purpose of the slotted floor is to allow the animal wastes to fall down to the pits. The slotted floor also allows the air to circulate via the two pits under the pen rows. Manure was collected in two pits under the pens. The under-floor manure pit is drained to a waste lagoon located approximately 20 m west of the building.



Figure 4-5 Photograph of the pen showing the slotted floor.

Ground feed is manually supplied to the feeders, which are designed to allow the animal to receive a certain amount of feed based on the movement from the animal head (Fig. 4-6).



Figure 4-6 Feeders filled with ground feed.

The barn is equipped with a mechanical ventilation system (Figs. 4-7 to 4-9). Ventilation air enters through 21 sidewall inlets (0.53 m wide each) distributed along the two sidewalls, passes through the two underfloor pits running longitudinally under the pens, and is exhausted by three 0.61-m main exhaust fans at one end of the building, in addition to one auxiliary fan for high temperature conditions. The temperature inside the barn is typically set to range from 19 to 25°C, and maintained by a mist system nozzles and climate control system at ceiling height. Supplementary heat is provided by two 51.3 kW gas heaters located in the middle of the building.



Figure 4-7 Air inlets: (a) outside and (b) inside.



Figure 4-8 Ventilation fans.



Figure 4-9 Supplemental heaters and environment control unit.

A regular maintenance procedure is followed in the facility. On a weekly basis, the animals are released from their pens for weighing and cleaning; at this time, the interior of the facility is cleaned so that all waste products and accumulated materials are forced off each individual enclosure and through the slotted floor, which is also cleaned. After this procedure, the animals are directed back into their pens. Other tasks include regular inspection of the facility and animals, as well as the manual refilling of the feeders with swine diet. Air sampling equipment was positioned such that maintenance issues did not affect sampling and measurement.

In order to obtain the sample material needed to perform the planned tests, a variety of samples were collected from the animal facility. Samples of airborne particles, swine diet, and settled material were obtained from the building.

4.3.2 Air sampling procedure

The following parameters were measured: (1) size distribution and number concentration of airborne particles; (2) mass concentration of particles; (3) net charge-to-mass ratio; (4)

temperature and relative humidity; and (4) true density of particles. In general, samplers and/or measurement devices were located at or near the center of the building (Fig. 4-10).



Figure 4-10 Instruments used to characterize the aerosol particles inside the animal building.

The size distribution and number concentration of the airborne particles were monitored by using an Aerodynamic Particle Sizer® (APS) spectrometer (Model 3321, TSI Inc., Shoreview, MN). This spectrometer measures the equivalent aerodynamic diameter (EAD) of particles from 0.54 to 20 μm , and uses an air sampling rate of 1.0 L/min. The APS was located near the center of the building, 360 (1 min) samples were taken during the study period. The particle size distributions (number and mass) were analyzed by calculating the following statistics:

a. Mean diameter for count (or count mean diameter)

$$\bar{d}_p = \frac{\sum n_i d_i}{\sum n_i} \quad (4.1)$$

b. Standard deviation (SD)

$$\sigma = \left(\frac{\sum n_i (\bar{d}_p - d_i)^2}{\sum n_i - 1} \right)^{0.5} \quad (4.2)$$

c. Geometric mean diameter (d_g or GMD) for count

$$d_g = \exp\left(\frac{\sum n_i (\ln d_i)}{\sum n_i}\right) \quad (4.3)$$

d. Geometric standard deviation (σ_g or GSD)

$$\sigma_g = \exp\left(\frac{\sum n_i (\ln d_i - \ln d_g)^2}{N-1}\right)^{0.5} \quad (4.4)$$

The mass concentration was measured by the Tapered Element Oscillating Microbalance (TEOM) (Series 1400a Ambient Particulate Monitor, Rupprecht & Patashnick Co., Inc., East Greenbush, NY); 145 1-min samples were taken during the study period. The mass concentration was also measured by filter samplers (37-mm diameter filter inside a plastic filter holder). For each test, three samplers were located at 1.5 m above the floor in the middle of the central alley. Three replicates were taken in this study. The sampling airflow rate (2 L/min) for each sampler was controlled with a critical orifice (Model SO-0, BGI Inc.). Sampling period was 60 min. The dust collection filters were preconditioned in a container with constant humidity (50% \pm 5%) and temperature (25°C \pm 3°C) for 24h, weighed, and then placed in the same container again under the same relative humidity and temperature for 24 h after sampling. This conditioning was done to minimize the effect of humidity on the weights of the filters. The conditioned filters were weighed in an electronic microbalance (Model AG245, Mettler-Toledo, Hightstown, N.J.) with sensitivity of 0.01 mg.

The net charge-to-mass ratio of aerosol particles was measured using the dynamic Faraday cage sampler described in Chapter 3. These measurements were done during the months of October to December, 2006.

Temperature and relative humidity were measured using a HOBO® U12 Logger (Onset Computer, Bourne, MA) with a manufacturer stated accuracy of $\pm 0.35^{\circ}\text{C}$; ambient temperature and relative humidity were recorded for the length of study (October, 2006 – February, 2007).

The true density of dust particles and feed particles was measured with a multipycnometer (Quantachrome Instruments, Boynton Beach, FL). The dust was collected from different surfaces inside the building such as the air inlets, shutters, metal grids, etc. Feed samples were collected randomly from the feeders; three replicates were taken in this study.

4.4 Results and Discussion

4.4.1 Net charge-to-mass ratio

The measured net charge-to-mass ratio was $+0.68 \text{ mC/kg}$ with $\text{SD} = 0.31 \text{ mC/kg}$. The magnitude of the charge of the airborne particles in livestock buildings seemed to be affected by the environmental conditions and activities inside the buildings.

4.4.2 Particle mass concentration

Values of total dust concentration (TDC) inside the animal building are summarized in Table 4-4. Shown are the mean values for the TEOM, filter samplers, and dynamic Faraday-cage sampler. The mean values are close to each other and ranged from 0.89 mg/m^3 for the TEOM to 1.0 mg/m^3 for the filter samplers. The values are lower than the TLV of 10 mg/m^3 for total dust (ACGIH, 1993). They are also lower than the exposure limit of 2.4 mg/m^3 proposed by Donham et al. (1989).

Table 4-4 Measurements of total dust concentration (TDC, mg/m³).

Technique	TDC	SD
TEOM	0.89	0.46
Filter sampler	1.0	0.25
Dynamic Faraday-cage sampler	0.99	0.43

4.4.3 Temperature and humidity

The inside air temperatures ranged from 22.2°C to 25.6°C with a mean of 24.5°C (SD=0.33°C). The inside relative humidity ranged from 35.4% to 63.8% with a mean of 53.5% (SD = 6.3%). The air temperature and relative humidity outside the barns were obtained from the nearest weather station, about 20 km away. The outside air temperatures at the sampling time ranged from 10.1°C to 13.5°C with a mean of 11.46°C (SD = 1.8°C), and the outside RH ranged from 36% to 69% with a mean of 47.7% (SD = 18.5%).

4.4.4 True particle density

Measured true density using the Multipycnometer for swine house dust and swine feed were 1.84 g/cm³ (SD = 0.03) and 1.53 g/cm³ with (SD = 0.05), respectively. The true density was needed for the APS in order to convert the particle number concentration to particle mass concentration.

4.4.5 Size distribution

As indicated above, the size distribution, number concentration, and mass concentration of the airborne particles were monitored by using the APS spectrometer. Figure 4-11 presents the particle size distribution inside the building based on number concentration. For this distribution, the GMD was 0.89 µm and the GSD was 1.81 (Table 4-5).

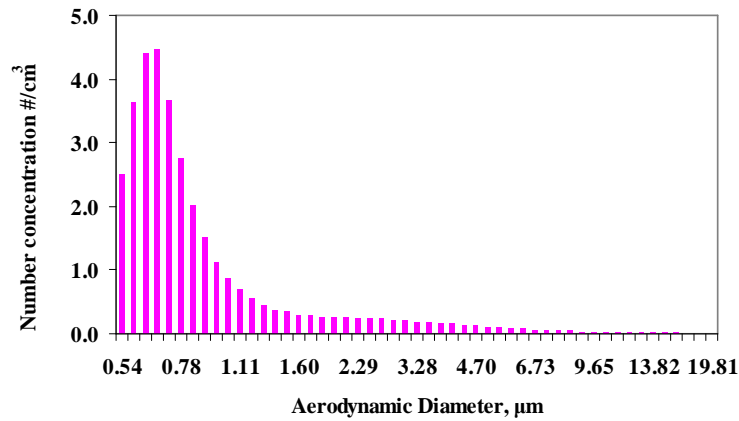


Figure 4-11 Measured particles size distribution based on number concentration (inside the building), average of 360 samples.

Table 4-5 Statistics of the size distribution of airborne particles inside the building (for 360 samples).

Parameter	Number Distribution			Mass Distribution		
	Range	Mean	SD	Range	Mean	SD
Median Diameter (µm)	0.64-1.25	0.71	0.11	8.72-12.3	11.24	0.86
Mean Diameter (µm)	0.82-2.33	1.21	0.34	8.74-11.5	10.75	0.65
Geometric Mean Diameter (µm)	0.71-1.51	0.89	0.17	6.51-10.3	9.34	0.84
Geometric Standard Deviation	0.83-2.42	1.81	0.29	1.70-10.0	2.11	1.48

Figure 4-12 shows the particle size distribution inside the building based on mass concentration. The GMD was 9.34 µm and the GSD was 2.11 (Table 4-5). The GMD was close to published values for other swine barns. Donham and Gustafson (1982) calculated a GMD of 11 µm from 17 swine buildings; Donham et al. (1986) reported a GMD of 10.7 µm in four finishing barns.

The cumulative percentage of mass concentration for the particles with size range 0.54-20 μm (Fig. 4-13) shows that a major fraction of the particles were larger than 10 μm (55%, by mass) and larger than 2.5 μm (95%, by mass). This indicates that a greater part of the dust mass would have high probability of settling out of the air or being collected in the nasal and pharyngeal regions if inhaled. Consequently, only a small proportion will penetrate into the more sensitive lower respiratory regions where greater damage can occur.

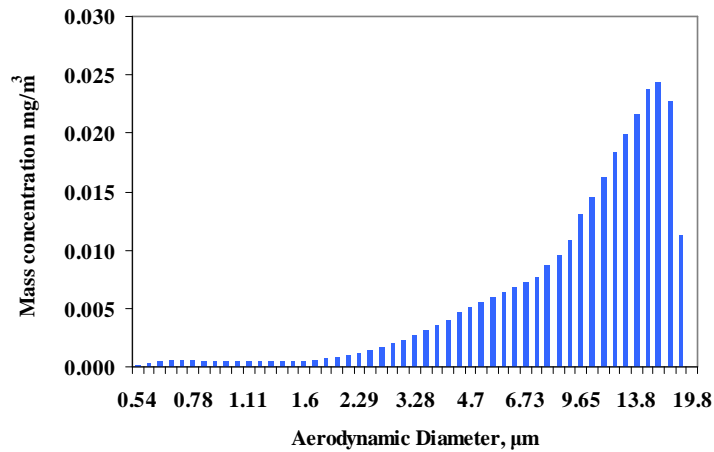


Figure 4-12 Measured particle size distribution inside the building based on mass concentration, average of 360 samples.

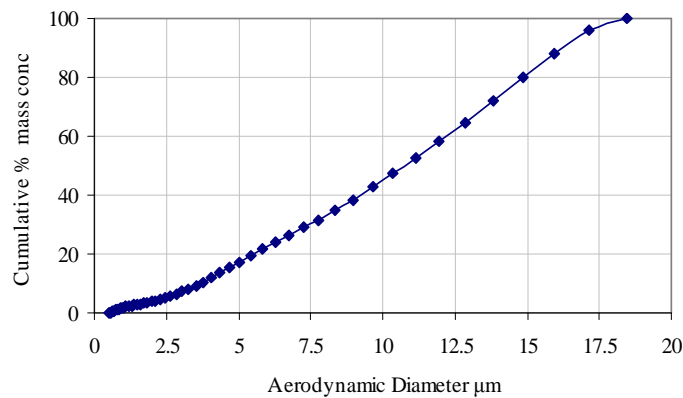


Figure 4-13 Measured cumulative percentage of particles size distribution based on mass concentration, average of 360 samples.

4.5 Conclusions

This research measured the particle concentration, particle size distribution, electrostatic charge, and true density of particles in a swine finishing building. The following conclusions were drawn from the study:

- The overall mean dust concentration in the swine barn was 0.89 mg/m^3 (SD = 0.45 mg/m^3). This value is lower than the established threshold limit value proposed by Donham et al. (1989), indicating that the air quality in this building was generally acceptable.
- The overall geometric mean diameter of particles (GMD), on a mass basis, was $9.34 \text{ }\mu\text{m}$ (SD = 0.84) and the geometric standard deviation GSD was $2.11 \text{ }\mu\text{m}$ (SD = 1.48). The GMD was close to published values for swine barns.
- The measured net charge-to-mass ratio was $+0.68 \text{ mC/kg}$ with SD = 0.31 mC/kg . The magnitude of charge of the airborne particles in livestock buildings were affected by many variables like the environmental conditions and the activities inside the buildings.
- Measured true density for swine house dust and swine feed were 1.84 g/cm^3 (SD = 0.03) and 1.53 g/cm^3 with (SD = 0.05) respectively.

4.6 References

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CHAPTER 5 - EFFECTIVENESS OF ELECTROSTATICALLY-CHARGED WATER SPRAY IN REDUCING DUST CONCENTRATION IN ENCLOSED SPACES

5.1 Abstract

The effectiveness of electrostatically charged water spray in reducing dust concentration was investigated in an enclosed experimental chamber (L=3.6 m, W=2.4 m, H=2.4 m). Test particles (i.e., corn starch, NaHCO₃) were first dispersed into the chamber by using a pressurized canister. Charged water droplets were then sprayed into the chamber. The size distribution, number concentration, and mass concentration of the test particles were measured with an Aerodynamic Particle Sizer™ (APS) spectrometer and a Tapered Element Oscillating Microbalance (TEOM).

From the APS and TEOM data, the particle removal efficiency for the charged water spray was determined. The performance of charged water spray was also compared with that of uncharged water spray and no water spray. Results showed that the charged water spray treatment was significantly more effective than either the uncharged water spray or no water spray treatments. The particle removal efficiency of the charged water spray (4 min spray duration, 120 mL/min), based on mass, ranged from 88% to 92% for particles $\leq 10 \mu\text{m}$ equivalent aerodynamic diameter and from 34% to 70% for particles $\leq 2.5 \mu\text{m}$ equivalent aerodynamic diameter.

5.2 Introduction

Poor air quality is a growing concern in livestock confinement buildings. A growing body of literature has documented the health problems among workers in these operations. Donham (1999), for example, reported the following statistics on swine confinement workers: (1) at least 60% of workers surveyed have acute or subacute respiratory symptoms, including dry cough, chest tightness, and wheezing on exposure to the work environment; irritation of the nose, eyes, and throat; and stuffy nose and throat; (2) at least 25% of the workers surveyed have periodic, acute, febrile episodes with fever, headache, muscle aches, and pains, chest tightness, and cough; and (3) at least 25% of the workers surveyed experience chronic bronchitis, occupational (nonallergenic) asthma, and noninfectious chronic sinusitis. In addition, previous researchers (Donham et al., 1989; Donham et al., 1995; Reynolds et al., 1996) have suggested the following exposure limits for swine confinement workers: 2.4 mg/m³ total dust and 0.23 mg/m³ respirable dust.

Air quality in livestock buildings should be improved to prevent occupational health problems. Engineering control strategies include: (1) reducing emission or generation rates of the air contaminants (i.e., source control); (2) dilution and/or effective room air distribution (i.e., ventilation control); and (3) air cleaning (i.e., removal control). Source control strategies for dust include use of feed additives (fat or oil), cleaning of dusty surfaces, and spraying water or oil over dusty surfaces. Ventilation control includes increasing ventilation rate, purge ventilation, and effective room air distribution systems. Air cleaning strategies include use of air filters, ionizers, wet scrubbers, or other air cleaners. Dust reduction efficiencies that have been reported with these strategies have ranged from 15% for weekly washing of pigs and floors, to 23% with

ionizers, to 76% with a rapeseed oil spray (CIGR, 1994). Other reports of ionizer efficiency have ranged from 31% (Czarick et al., 1985) to 92% (Mitchell, 1998).

A potential dust reduction method is spraying charged water into the airspace. Hoenig (1977) and Gillespie (1955) have shown that most dust particles acquire electrostatic charges as they are dispersed into the air. The polarity and magnitude of the charges on these particles depend upon their size and origin (Hoenig, 1977; Hassler, 1978). Therefore, particle collection efficiency of water droplets may be significantly enhanced via electrostatic forces of attraction if the droplets are charged to the opposite polarity (Mathai, 1983).

Mathai (1983) and Hinds (1999) described the process when an aerosol particle approaches a water droplet. The particle may directly collide with the droplet (impaction), barely touch the droplet (interception), or entirely miss the droplet. The diameter of the particle is the dominant factor that determines which of these mechanisms is the most important. Mathai (1983) also indicated that controlling and increasing the electrostatic force of the water droplet will dramatically increase the collection of particles with diameter between 0.1 and 2-3 μm . Charged droplets can also enhance the other collection mechanisms by increasing the attraction between the particle and water droplet.

The major objective of this study was to evaluate the potential of electrostatically-charged water spray in controlling dust particles in enclosed spaces. Specific objectives were to:

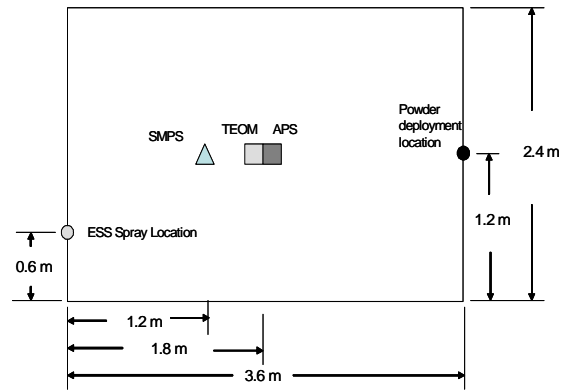
- (1) Compare charged water spray, uncharged water spray, and no water spray in terms of dust removal efficiency; and
- (2) Determine the effects of spray duration, spraying method, charge polarity, ambient relative humidity, and initial dust concentration on the dust collection efficiency of water spray.

If found effective, a system that would use charged water spray will be developed and evaluated in a livestock building.

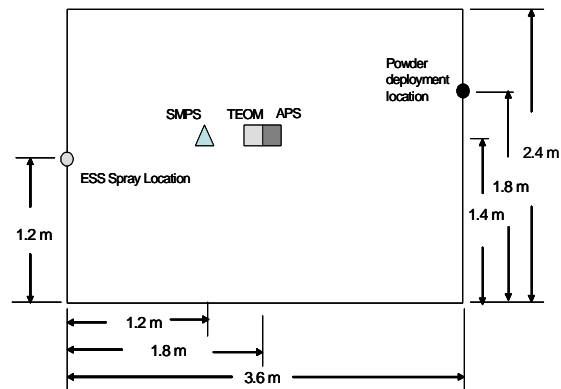
5.3 Materials and Methods

Experiments were conducted in an enclosed experimental chamber (Fig. 5-1), which was maintained at normal room temperatures. The experimental chamber was located inside another insulated chamber; both chambers were located at an environmentally controlled laboratory. This setup was used to minimize air convection currents in the chamber due to the possible temperature gradient outside the chamber; therefore, the possibility of creation of temperature gradient inside the chamber during spraying (0.5 to 1 °C at 4 min spray) was negligible because the tests were done in isothermal conditions. However, there will be some air movement inside the chamber, particularly during the water spraying process.

The chamber was equipped with particle measuring instruments, including an Aerodynamic Particle Sizer™ (APS) spectrometer (Model 3321, TSI Inc., St. Paul, MN), a Scanning Mobility Particle Sizer™ (SMPS) spectrometer (Model 3936, TSI Inc., St. Paul, MN), and Tapered Element Oscillating Microbalance (TEOM) (Series 1400a Ambient Particulate Monitor, Rupprecht & Patashnick Co., Inc., East Greenbush, NY).



(a)



(b)

Figure 5-1 Schematic diagram of the experimental chamber and setup: (a) elevation and (b) plan view.

5.3.1 Measurement of size distribution

The size distribution and number concentration of the airborne particles were monitored by using the APS spectrometer. This spectrometer measures the equivalent aerodynamic diameter (EAD) of particles from 0.54 to 20 μm , and uses an air sampling rate of 1.0 L/min. The spectrometer was connected to a dilution unit, which was set at a 100:1 dilution ratio. Both the dilution unit and the APS were located near the center of the experimental chamber (Fig. 5-1). In some experiments, the SMPS spectrometer was used to measure the concentration of particles from 20 to 835 nm equivalent mobility diameter.

5.3.2 Test particles

Two types of test particles were considered: corn starch and sodium bicarbonate (NaHCO_3). These particles were selected based on safety, size distribution, and relative net charge-to-mass ratio. Whereas results with these particles may not be the same as with typical dust in animal housing because of differences in shapes, sizes, and relative charge-to-mass ratios, these particles will give an indication of the behavior of charged spray under controlled conditions. The particle densities, as measured with a multipycnometer (Quantachrome Instruments, Boynton Beach, FL) were 1.53 g/cm^3 (standard deviation, $\text{SD}=0.06 \text{ g/cm}^3$) and 2.22 g/cm^3 ($\text{SD}=0.02 \text{ g/cm}^3$) for corn starch and NaHCO_3 , respectively. The test particles also have different relative electrostatic charges. For example, when dispersed into the experimental chamber by using a pressurized canister equipped with an aluminum nozzle, the net charge-to-mass ratios (as measured with a dynamic Faraday-cage sampler) were -0.11 mC/kg ($\text{SD}=0.07 \text{ mC/kg}$) and $+0.20 \text{ mC/kg}$ ($\text{SD}=0.001 \text{ mC/kg}$) for corn starch and NaHCO_3 , respectively. The test particles also differed in the initial size distribution (Figs. 5-2 and 5-3; Table 5-1), with corn starch having a larger geometric mean diameter (GMD) than NaHCO_3 .

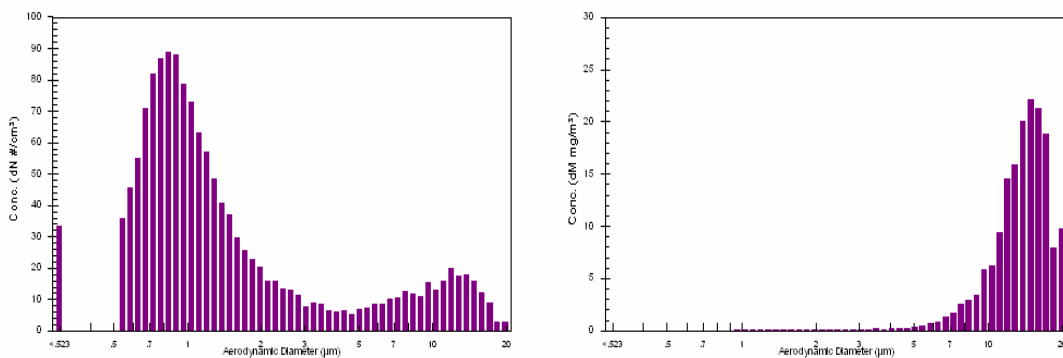


Figure 5-2 Initial particle size distribution of dispersed corn starch (based on number and mass) as measured by the Aerodynamic Particle Sizer™ spectrometer.

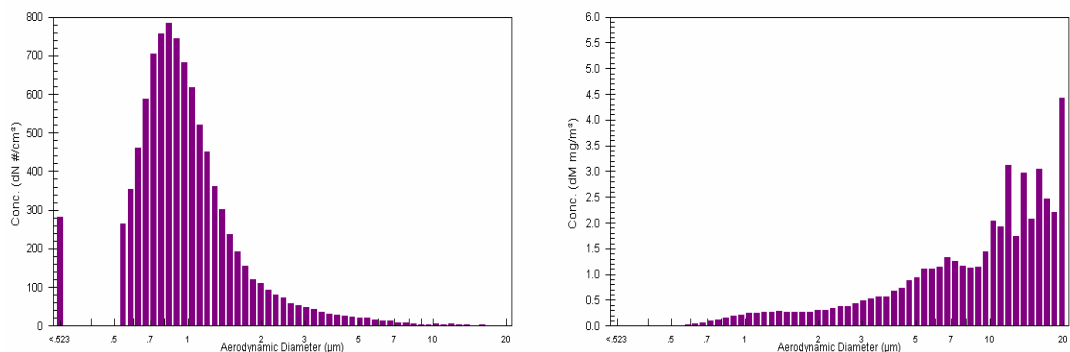


Figure 5-3 Initial particle size distribution of dispersed NaHCO_3 (based on number and mass) as measured by the Aerodynamic Particle Sizer™ spectrometer.

Table 5-1 Statistics of the initial particle size distributions of dispersed corn starch and NaHCO_3 .

Parameter	Corn Starch				NaHCO_3			
	Number		Mass		Number		Mass	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Median Diameter (μm)	1.36	0.18	14.08	0.41	0.89	0.01	7.61	0.88
Mean Diameter (μm)	3.84	0.75	13.58	0.39	1.12	0.00	7.85	0.68
Geometric Mean Diameter, GMD (μm)	2.07	0.32	13.05	0.50	0.98	0.01	6.14	0.53
Geometric Standard Deviation, GSD	2.93	0.25	1.37	0.04	1.58	0.02	2.22	0.04

5.3.3 Electrostatically-charged water spray

The charged water spray was generated by using a commercially available electrostatic spraying system (Electrostatic Spraying Systems, Inc., Watkinsville, GA 30677 USA), which is based on induction charging. The spraying system was operated at a liquid flow rate of 120

mL/min (water tank pressure of 15 psig). The voltage for the induction ring was 1000 VDC. The droplet GMD was 21.0 μm and GSD was 1.71 μm as measured by a cascade impactor (MOUDI 110, MSP Corp., Shoreview, MN). In this study, only one nozzle was used; however for practical application, more than one nozzle may have to be used.

5.3.4 Experimental design and procedure

Six sets of experiments were conducted. Each of the sets of experiments is described below. Most experiments used the negatively-charged water spray with a charging level of approximately -6.5 mC/L. Each experiment had at least three replicates; however, if results were quite variable, additional replicates were conducted to reduce the standard deviation.

The first set of experiments was conducted to compare charged water spray, uncharged water spray, and no water spray. The no-water-spray treatment served as the control and was used to account for removal of particles by gravitational settling. Both the charged-water-spray and uncharged-water-spray treatments involved spraying water into the chamber continuously for 4 min. The second set of experiments determined the effect of spray duration on dust removal efficiency. In this set, the spraying system was operated at spray durations of 2, 4, and 6 min with a liquid flow rate of 120 mL/min. The equivalent total volumes of water sprayed into the chamber were 240, 480, and 720 mL for the 2-, 4-, and 6-min spray durations, respectively. The third set of experiments evaluated the effect of spray method (i.e., continuous vs intermittent) on removal efficiency with charged water spray. In the continuous spray method, the spraying system was operated continuously for 4 min. In the intermittent method, on the other hand, the spraying system was operated for 1 min 4 times with 1 min interval between sprays. The fourth set of experiments compared the negatively-charged with positively-charged water sprays using spray duration of 4 min. The positively-charged spray was operated with a

charging level of approximately +7.2 mC/L. The fifth set considered the effect of ambient relative humidity (i.e., 40 vs 80%). The relative humidity inside the chamber was stabilized to 20% for all tests; however, for the 80% test the relative humidity inside the chamber was increased to 60% using an ultrasonic humidifier. It was found that spraying for 4 min will increase the relative humidity inside the chamber by approximately 20%. The sixth set of experiments determined the effect of mass dispersed (i.e., 10, 20, and 30 g) on removal efficiency of charged water spray.

For each experiment, the chamber was prepared by cleaning the surfaces and running its air filtration system. The ventilation and air filtration systems were not operated during the experiment, so that air exchange in the room was primarily through natural infiltration/exfiltration. As such, results could be different in spaces with ventilation rates equivalent to typical animal housing. The concentration of particles was measured (1 min/sample) with the APS before dispersion of the particles and 2 min after dispersion. The measured concentration at 2 min after dispersion was considered as the initial particle concentration. The total mass concentration was also monitored continuously using the TEOM starting from 2 min before spraying until 60 min after spraying. The TEOM temperature was set at 50°C to ensure evaporation of water droplets entering the TEOM sampling inlet. The particles were dispersed by using a pressurized canister at 80 psig (time $t = 0$). For all sets of experiments (except the sixth set, which considered the effect of mass deployed), a nominal mass of 20 g was used; the actual mass deployed ranged from 7.4 to 12.5 g for corn starch and from 2.7 to 8.3 g for NaHCO₃. Dispersion took approximately 2 sec. To further disperse the particles inside the chamber, two mixing fans inside the chamber were operated for about 1 min after deployment of the particles.

The charged water droplets were sprayed into the chamber starting at $t=2$ min (i.e., 2 min after particle deployment). The concentration of the airborne particles was measured from $t=10$ min to $t=60$ min (1 sample/min). The measured concentration at $t=10$ min was considered in calculating the removal efficiency for all tests except for the second set of experiments, which determined the effect of spray duration test. In the second set, sampling was taken 6 min after the end of spraying and the concentrations at $t=10, 12,$ and 14 min were used to calculate the removal efficiency for spray durations of 2, 4, and 6 min, respectively. This procedure was done so that the time periods between the end of spraying and the sampling time used for calculating removal efficiency were consistent for the three spray durations.

5.3.5 Data analysis

From the number concentration data from the APS, the corresponding mass concentration for each size range was calculated by using the following equation

$$C_m = \frac{\pi}{6} \rho_o d_a^3 C_n \quad (5.1)$$

where C_m is the mass concentration, C_n is the number concentration, ρ_o is the standard density (1000 kg/m^3), and d_a is the EAD. The removal efficiency for a given size range was determined from the mass concentration, that is,

$$\eta_d = \frac{C_{md,2} - C_{md,10}}{C_{md,2}} \quad (5.2)$$

where η_d is the removal efficiency for certain size range based on mass concentration, $C_{md,2}$ is the mass concentration for the particle size range before spraying (i.e., at $t=2$ min), and $C_{md,10}$ is the mass concentration for the particle size range after spraying (i.e., at $t=10$ min). The removal efficiencies for particles $\leq 10 \text{ } \mu\text{m}$ EAD (η_{10}) and for particles $\leq 2.5 \text{ } \mu\text{m}$ EAD ($\eta_{2.5}$) were

determined based on the mass concentrations of particles $\leq 10 \mu\text{m}$ EAD and of particles $\leq 2.5 \mu\text{m}$ EAD, respectively.

The removal efficiency was also determined from the mass concentrations measured by the TEOM:

$$\eta_t = \frac{C_{m,2} - C_{m,10}}{C_{m,2}} \quad (5.3)$$

where η_t is the removal efficiency based on mass concentration for total suspended particles (TSP), $C_{m,2}$ is the mass concentration before spraying (i.e., at $t=2$ min), and $C_{m,10}$ is the mass concentration after spraying (i.e., at $t=10$ min).

The removal efficiencies were analyzed by using PROC GLM of SAS (Version 9.1, SAS Institute, Inc., Cary, NC). Treatment means were compared by using Duncan's Multiple Range Test at a level of significance of 5%.

5.4 Results and Discussion

5.4.1 Effectiveness of charged water spray

Figures 5-4 and 5-5 show the particle size distributions, based on mass concentrations, for NaHCO_3 and corn starch, respectively, before and after spraying of the charged water droplets. The charged water spray reduced the mass concentrations for all sizes. As expected, the reduction in mass concentration increased with increasing particle size. It should be noted that the reduction in concentration was due to the combined effects of the charged water spray and gravitational settling of the test particles.

Table 5-2 summarizes the geometric mean diameters (GMD) and geometric standard deviations (GSD) of the distributions in Figures 5-1 and 5-2, and also the distributions for the no-water-spray treatment. For each type of particle, the control and the charged-water-spray

treatment did not significantly differ ($P>0.05$) in the mean initial GMD (i.e., at $t=2$ min). At $t=10$ min, the charged-water-spray treatment had a significantly lower ($P<0.05$) mean GMD than the control. The lower GMD for the charged-water-spray treatment is due to the removal of the large particles by the charged-water droplets. For each treatment, comparison of the initial GMD and the GMD at $t=10$ min showed a significant reduction ($P<0.05$). The reduction was higher for the charged-water-spray treatment compared with the control, again because of the additional removal of the large particles by the charged water droplets.

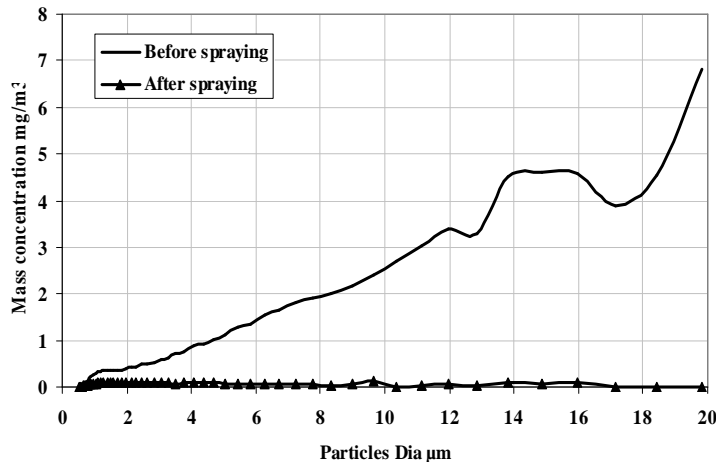


Figure 5-4 Mass size distribution of NaHCO_3 , before and after charged-water spraying, as measured by the Aerodynamic Particle SizerTM spectrometer. The duration of spraying was 4 min at 120 mL/min.

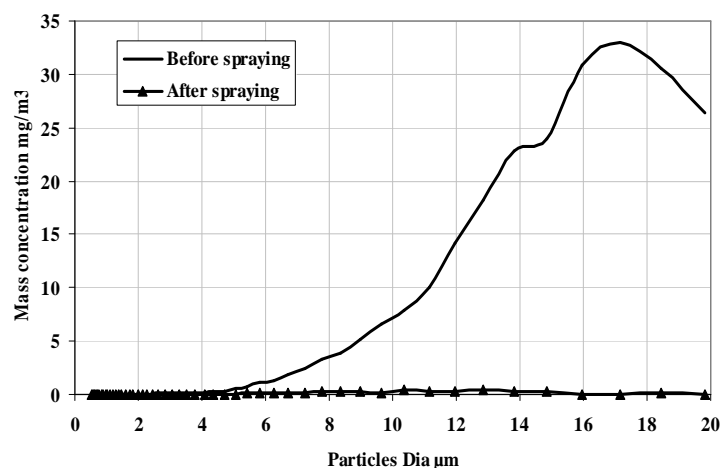


Figure 5-5 Mass size distribution of corn starch, before and after charged-water spraying, as measured by the Aerodynamic Particle Sizer™ spectrometer. The duration of spraying was 4 min at 120 mL/min.

Table 5-2 Geometric mean diameter (GMD), mass basis, and geometric standard deviation (GSD) for the charged-spray treatment (4 min spray duration, 120 mL/min) and control (no water spray).¹

Treatment	Corn Starch				NaHCO ₃			
	Initial (t=2 min)		At t=10 min		Initial (t=2 min)		At t=10 min	
	GMD ² μm	GSD	GMD ² μm	GSD	GMD ² μm	GSD	GMD ² μm	GSD
Charged water spray	13.1 a	1.37	7.3 a	1.99	6.1 a	2.22	2.4 a	2.11
Control (no water spray)	13.0 a	1.40	10.0 b	1.59	5.9 a	2.23	4.0 b	2.20

¹Particle concentrations were measured with the Aerodynamic Particle Sizer™ spectrometer.

²Column means with the same letter are not significantly different at 5% level of significance

Table 5-3 summarizes the removal efficiencies (η_{10} and $\eta_{2.5}$) for corn starch and NaHCO_3 . In general, the charged-water-spray treatment had significantly ($P < 0.05$) higher particle removal efficiency than either the control (i.e., no water spray) or the uncharged-water-spray treatment. For particles $\leq 10 \mu\text{m}$ EAD, the charged water spray resulted in mean removal efficiencies of 87.7% for NaHCO_3 and 91.7% for corn starch. For particles $\leq 2.5 \mu\text{m}$ EAD, on the other hand, the charged water spray resulted in removal efficiencies of 68.5% for NaHCO_3 and 33.5% for corn starch.

Particles, particularly the large ones, are also removed by gravitational settling. For example, particles with $10 \mu\text{m}$ EAD have terminal settling velocities of 0.30 cm/s under normal conditions of temperature and pressure. For particles $\leq 10 \mu\text{m}$ EAD, the control (i.e., no water spray) had mean removal efficiencies of 37.3% for NaHCO_3 and 52.8% for corn starch. The lower removal efficiency for NaHCO_3 could be due to its lower initial GMD, compared with that of corn starch. As expected, for the control, the removal efficiency for particles $\leq 2.5 \mu\text{m}$ EAD, which have lower settling velocities than particles $\leq 10 \mu\text{m}$, were considerably lower at about 28%.

It was surprising that the uncharged water spray was not effective compared with the control even for the larger particles. Although the η_{10} for corn starch was 62.3%, it was only 31.1% for NaHCO_3 . In addition, the $\eta_{2.5}$ values for the uncharged-water-spray treatment were close to zero, indicating that the water droplets were unable to collide with the small dust particles. The evaporating water droplets could also have contributed to the mass of particles $\leq 2.5 \mu\text{m}$ EAD, resulting in negligible removal efficiency for the solid particles. This also could be due to the measurement device (APS) counting water particles as well as dust.

Table 5-3 Removal efficiencies (mass basis) for corn starch and NaHCO₃ of charged water spray (4 min duration at 120 mL/min), uncharged water spray (4 min duration at 120 mL/min), and no water spray.¹

Treatment	Corn Starch				NaHCO ₃			
	η_{10}		$\eta_{2.5}$		η_{10}		$\eta_{2.5}$	
	Mean ²	SD	Mean ²	SD	Mean ²	SD	Mean ²	SD
Charged water spray	91.7 a	2.0	33.5 a	8.5	87.7 a	3.2	68.5 a	7.5
Uncharged water spray	62.3 b	6.8	0.76 b	1.3	31.1 b	5.9	0.35 b	0.6
Control (no water spray)	52.8 b	4.0	28.4 a	6.5	37.3 b	4.3	27.9 c	1.3

¹Particle concentrations (size range of 0.54-20 μm) were measured with the Aerodynamic Particle SizerTM spectrometer.

²Column means with the same letter are not significantly different at 5% level of significance.

Further investigations (Table 5-4) were done to measure the removal efficiency using TEOM (total suspended particles). Figures 5-6 and 5-7 show the removal efficiency vs. time for both powders. At t=10 min, the uncharged water and the no-spray treatments were similar in removal efficiency and were considerably less effective than the charged water spray treatment.

Table 5-4 Removal efficiencies (mass basis - total suspended particles) for corn starch and NaHCO₃ of charged water spray (4 min duration at 120 mL/min), uncharged water spray (4 min duration at 120 mL/min), and no water spray.¹

Treatment	Corn Starch		NaHCO ₃	
	η^2	SD	η^2	SD
Charged water spray	98.1 a	0.004	94.0 a	0.02
Uncharged water spray	89.2 b	0.03	64.4 b	0.01
Control (no water spray)	84.8 b	0.04	55.8 c	0.02

¹Particle concentrations were measured with the TEOM.

²Column means on removal efficiency followed by the same letter are not significantly different at 5% level of significance. The efficiency was evaluated at t=10min.

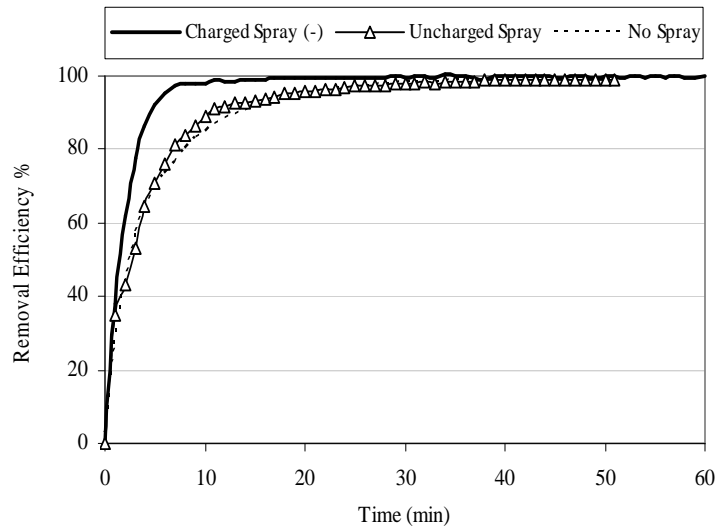


Figure 5-6 Removal efficiency of corn starch for total suspended particles, as measured using TEOM

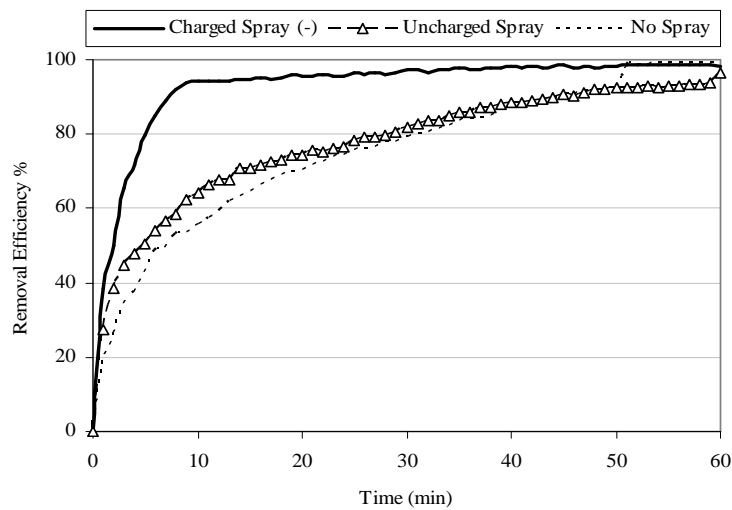


Figure 5-7 Removal efficiency of NaHCO_3 for total suspended particles, as measured using TEOM.

Figure 5-8 summarizes the removal efficiency for the submicrometer particles (measured by the SMPS spectrometer). Compared with the control, the charged-water-spray treatment had

higher removal efficiency for the 20 to 835-nm mobility diameter; the difference was significant for NaHCO₃ but not for corn starch.

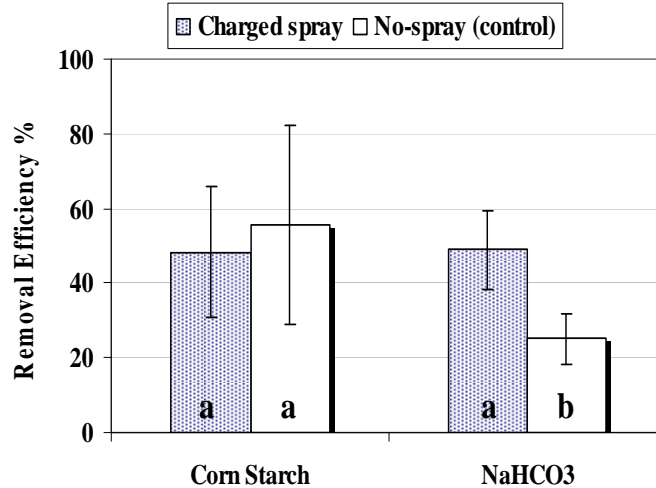


Figure 5-8 Removal efficiencies (mass basis) of the charged water spray for the small particles (20 to 835-nm mobility diameter) for corn starch and NaHCO₃ measured by the Scanning Mobility Particle Sizer™ spectrometer. Error bars represent one standard deviation. For each substance, bars with the same letter are not significantly different at 5% level of significance.

5.4.2 Effect of spray duration

Figures 5-9 and 5-10 compare the three spray durations in terms of the removal efficiency of the charged water spray. For corn starch, the removal efficiency ranged from negligible for small particles to more than 90% for the large particles. For NaHCO₃, on the other hand, the removal efficiency was greater than 55%, even for the small particles. Table 5.5 compares the three spray durations in terms of η_{10} and $\eta_{2.5}$. As expected, longer spray durations (i.e., 4 and 6 min), which have greater mass of water sprayed, had significantly ($P < 0.05$) higher dust removal efficiency than the shorter spray duration (i.e., 2 min). In general, the 4- and 6-min spray duration did not significantly differ ($P > 0.05$).

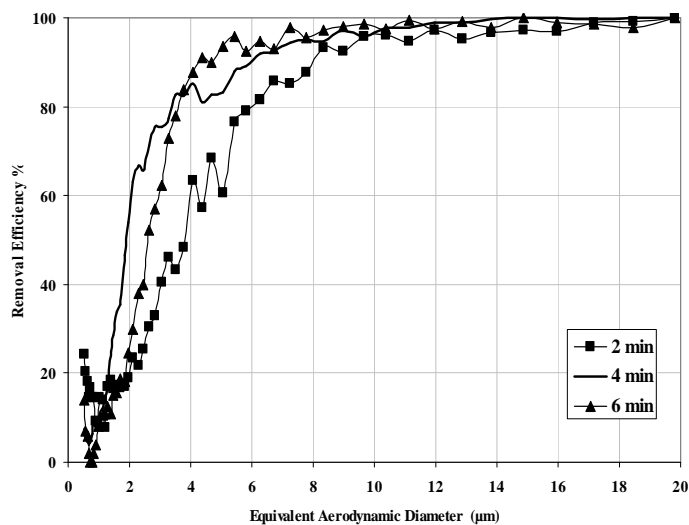


Figure 5-9 Removal efficiencies (mass basis) for corn starch with charged water spray with spray durations of 2, 4, and 6 min. The particle concentration was measured by the Aerodynamic Particle Sizer™ spectrometer.

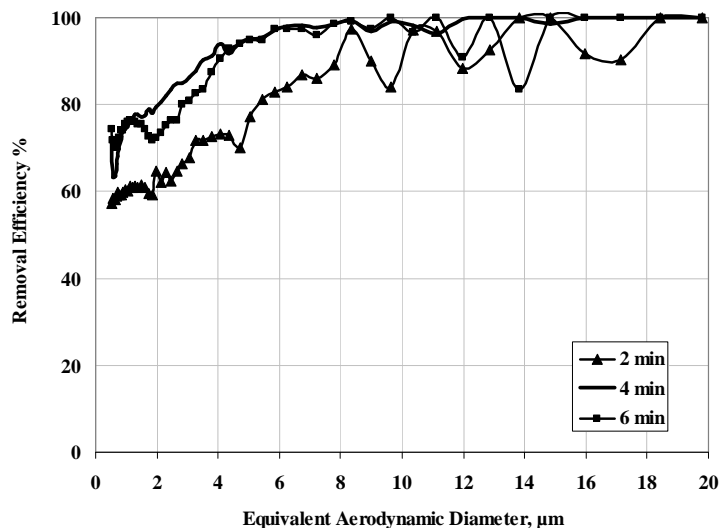


Figure 5-10 Removal efficiencies (mass basis) for NaHCO₃ with charged water spray with spray durations of 2, 4, and 6 min. The particle concentration was measured by the Aerodynamic Particle Sizer™ spectrometer.

Table 5-5 Effect of spray duration on removal efficiency of charged water spray.¹

Spray Duration (min)	Corn Starch				NaHCO ₃			
	η_{10}		$\eta_{2.5}$		η_{10}		$\eta_{2.5}$	
	Mean ²	SD	Mean ²	SD	Mean ²	SD	Mean ²	SD
2	83.9 b	2.1	18.0 b	9.9	76.1 b	5.2	61.3 b	3.6
4	92.6 a	1.2	38.2 a	5.7	91.1 a	1.8	74.8 a	3.7
6	92.2 a	1.9	19.3 b	10.9	89.1 a	3.8	74.5 a	4.7

¹Particle concentrations were measured with the Aerodynamic Particle Sizer™ spectrometer.

²Column means followed by the same letter are not significantly different at 5% level of significance.

5.4.3 Effect of continuous and intermittent water spray methods

Table 5-6 compares the continuous and intermittent sprays. The intermittent spray generally resulted in slightly greater removal efficiencies than the continuous spray, but the two spray methods did not significantly differ ($P>0.05$) in removal efficiencies.

Table 5-6 Effect of spray method on removal efficiency of charged water spray.¹

Spray method	Corn Starch				NaHCO ₃			
	η_{10}		$\eta_{2.5}$		η_{10}		$\eta_{2.5}$	
	Mean ²	SD	Mean ²	SD	Mean ²	SD	Mean ²	SD
Continuous	91.7 a	2.0	33.5 a	8.5	87.7 a	3.2	69.5 a	7.5
Intermittent	93.1 a	3.9	59.5 a	20.2	89.0 a	2.6	73.7 a	3.4

¹Particle concentrations were measured with the Aerodynamic Particle Sizer™ spectrometer.

²Column means followed by the same letter are not significantly different at 5% level of significance.

5.4.4 Effect of charge polarity

Table 5-7 summarizes the removal efficiencies for the negatively-charged and positively-charged water sprays. The two spray polarities did not significantly differ ($P>0.05$) in $\eta_{2.5}$ and

η_{10} for both powders. It was expected that the oppositely charged water droplet and particle will result in significantly higher removal efficiency due to the Coulombic forces. However, for large particles, there are other forces that still work to increase the removal efficiency even if both particles and droplets have the same charge polarity like the force of image charge in addition to other mechanical collection forces.

Furthermore, results showed that the charged water droplets collected the oppositely charge particles more efficiently for small particles compared with large particles since the electrostatic force, specifically the columbic force, will be the dominant collecting force for small particles.

Table 5-7 Effect of charge polarity on removal efficiency of charged-water spray.

Charge polarity (water droplet)	Corn Starch (slightly negative)				NaHCO ₃ (slightly positive)			
	η_{10}		$\eta_{2.5}$		η_{10}		$\eta_{2.5}$	
	Mean ¹	SD	Mean ¹	SD	Mean ¹	SD	Mean ¹	SD
Positive	90.6 a	7.1	47.4 a	3.8	82.9 a	1.9	65.7 a	2.7
Negative	91.7 a	2.0	33.5 a	8.5	87.7 a	3.2	69.5 a	7.5

¹Column means followed by the same letter are not significantly different at 5% level of significance.

5.4.5 Effect of ambient relative humidity

Table 5-8 compares the two levels of ambient relative humidity (i.e., 40% and 80%). In general, removal efficiency was lower for the 80% relative humidity than for the 40% relative humidity. For NaHCO₃, the difference between the two levels of humidity was not significant ($P>0.05$); for corn starch, on the other hand, the difference was significant ($P<0.05$). If the effect of electrostatic charge is not considered, high humidity is expected to enhance agglomeration of particles with each other which, in turn, will cause fast settling of particles due to the increase in

its size (Smorodin et al., 1999). High relative humidity, however, resulted in a decrease in the removal efficiency by the charged water spray. It is possible that the high relative humidity reduces to some degree interaction between particles and droplets.

Table 5-8 Effect of ambient relative humidity on removal efficiency of charged-water spray.

Relative humidity	Corn Starch				NaHCO ₃			
	η_{10}		$\eta_{2.5}$		η_{10}		$\eta_{2.5}$	
	Mean ¹	SD	Mean ¹	SD	Mean ¹	SD	Mean ¹	SD
80 %	86.9 a	2.2	3.2 a	2.7	83.3 a	4.3	61.0 a	5.6
40 %	91.7 b	2.0	33.5 b	8.5	87.7 a	3.2	69.5 a	7.5

¹Column means followed by the same letter are not significantly different at 5% level of significance.

5.4.6 Effect of mass of particles dispersed

Table 5-9 compares the three levels of mass of particles dispersed. There was no significant difference ($P>0.05$) between the 20 and 30g treatments in η_{10} and $\eta_{2.5}$. The 10g was significantly different ($P>0.05$) from 20 and 30g in η_{10} for NaHCO₃ and in $\eta_{2.5}$ for NaHCO₃ and corn starch. This result may be due to the increase in the coagulation between the particles themselves and the particles with the water droplets due to the decrease in the distances between them; this will enhance the collection mechanisms like impaction, interception, and the effect of the electrostatic forces.

Table 5-9 Effect of three levels of mass of particles dispersed (10, 20, 30g) on removal efficiency of charged-water spray.

Mass dispersed (g)	Corn Starch				NaHCO ₃			
	η_{10}		$\eta_{2.5}$		η_{10}		$\eta_{2.5}$	
	Mean ¹	SD	Mean ¹	SD	Mean ¹	SD	Mean ¹	SD
10	90.4 a	3.7	10.0 a	6.0	80.5 a	2.4	63.8 a	1.0
20	91.7 a	2.0	33.5 b	8.5	87.7 b	3.2	69.5 a	7.5
30	90.7 a	4.0	46.9 b	17.2	86.2 b	2.3	69.7 a	5.4

¹Column means followed by the same letter are not significantly different at 5% level of significance.

5.5 Conclusions

The effectiveness of electrostatically charged water spray in reducing dust concentration in enclosed spaces was evaluated. The following conclusions were drawn from this research:

- The charged water spray treatment was significantly more effective than either the uncharged water spray or no water spray treatments. For particles $\leq 10 \mu\text{m}$ equivalent aerodynamic diameter, the mean (mass) removal efficiencies for the charged water spray treatment (4-min spray duration) were 87.7% for NaHCO₃ and 91.7% for corn starch particles. For particles $\leq 2.5 \mu\text{m}$ equivalent aerodynamic diameter, the mean mass removal efficiencies were 68.5% for NaHCO₃ and 33.5% for corn starch.
- Longer charged-water-spray durations (4 and 6 min) resulted in significantly higher particle removal efficiency than the shorter (2 min) duration.
- The method of spraying charged water (i.e., continuous vs. intermittent) did not significantly influence particle removal efficiency.
- The charge polarity did not significantly influence particle removal efficiency.
- Particle removal efficiency was generally higher for the low ambient relative humidity (40%) than for the high relative humidity (80%).

- In some cases, particle removal efficiency increased with increasing mass of particles dispersed.

In general, results of the laboratory experiments indicate the potential of charged-water spray in controlling dust concentration within enclosed spaces. Future work will involve developing systems that could be used in actual buildings, including livestock buildings.

5.6 References

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CHAPTER 6 - MODELING THE PARTICLE COLLECTION EFFICIENCY OF CHARGED WATER SPRAY

6.1 Abstract

The collection mechanisms and theoretical models that have been developed for water sprays (charged and uncharged) were reviewed. A simple coagulation model was modified and used to predict the concentration of airborne dust in an enclosed airspace that was treated with charged water spray. From the predicted concentration, the collection efficiency of charged water spray was calculated. Predicted values of dust concentration and removal efficiency agreed well with measured values, indicating that the coagulation model can be used for charged water sprays.

6.2 Introduction

Air quality inside livestock buildings should be improved to ensure acceptable conditions for both the workers and livestock being housed. Engineering control strategies include source control, ventilation control, and air cleaning. Experimental results presented in Chapter 5 of this thesis have shown the potential of electrostatically-charged water spray in removing dust in an enclosed airspace.

The scrubbing process of a single droplet as a dust collector has been discussed theoretically in literature; however, only a few published papers have considered the overall effects of water sprays on the reduction of airborne particle concentrations. Moreover, only a limited number of those papers have related experimental results to theoretical analyses.

This study was conducted to predict airborne dust concentration in an airspace that was treated with charged water spray. Specific objectives were to:

1. Review the mechanisms that control the particle collection process and models that have been developed;
2. Predict the particle concentrations and removal efficiency associated with charged water sprays; and
3. Compare measured and predicted particle concentrations and removal efficiencies.

6.3 Literature Review

Various researchers have developed models to describe the collection of particles by uncharged and charged water droplets. Kraemer and Johnstone (1955) were the first to theoretically consider the removal of the charged dust by oppositely charged droplets. They determined the collection efficiency of charged droplets taking into account the Coulomb, image, and Stokes forces as well as the space charge effects. Nielsen and Hill (1976 a, b) calculated numerically the collection efficiency of charged droplets, taking into account the external electric field force and the electric dipole interaction force. Beizaie and Tien (1980) considered gravitational effects and concluded that gravity is dominant when the dust particles flow co-linear with the gravitational force. Brabec et al. (2005) developed a model that describes the effectiveness of using a high-pressure water-fogging system for grain dust control.

The problem of deposition on a collector droplet falling down and entrained by the flowing gas was studied by Wang et al. (1986 a, b); however, their solutions were restricted to 2-dimensional geometry only, and the flow field was determined from approximate equations. Schmidt and Loeffler (1992) solved the Navier–Stokes equations to determine the flow field near the collector, but these solutions were obtained for a fixed collector only. Sumiyoshitani (1996)

developed a 3-dimensional model for analyzing charge carrier motion around a charged spherical object in the presence of flow and electric field that may also be applicable for particle deposition.

Jaworek et al. (1997, 2002) studied the trajectories of dust particles in the vicinity of a charged droplet falling in a quiescent air. The differential equations of motion of the particle and the droplet were solved simultaneously, and the flow field near the droplet was determined from numerical solutions of the Navier–Stokes equations. Smorodin et al. (1999) developed a mathematical model to find the characteristic time of electro-diffusion coagulation between the particles and the collectors. Koyevnikova and Zimmels (2000) developed a more complex model using an array of stationary droplets and a single particle falling between them.

Simplified models have also been developed. Balachandran et al. (2001) obtained a model that describes the removal of particles by water spray (droplets) experimentally; the model was based on time constant for each process. Inculet et al. (1989) and Xiang (1997) developed a model describing the removal of particles by water spray (droplets); their model was based on the coagulation between the particles and the collectors.

6.3.1 Collection of particles by a single water droplet

In order for suspended particles to be removed from a gas (i.e., collected), the gas must pass through a zone in which the particles, under the influence of a force (or forces), would be diverted from the flow direction of the stream. The particles must remain under the influence of the collecting force(s) a sufficient length of time to be diverted and contact some collecting surface where they are removed from the stream (Licht, 1988). There are five major mechanisms of particle collection by water droplets: (1) interception; (2) inertial impaction; (3)

gravitational settling; (4) Brownian deposition; and (5) electrostatic attraction (Fig. 6-1). What follows is a brief description of each of these mechanisms.

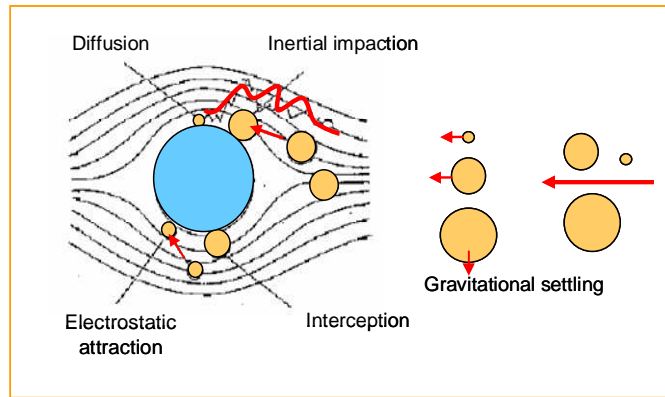


Figure 6-1 Schematic diagram showing the particle collection mechanisms by a water droplet.

Interception. Direct interception occurs when the fluid streamline carrying the particle passes within one-half of a particle diameter of the droplet. Regardless of the particle size, mass, or inertia, a particle will be collected if the streamline passes sufficiently close (Xiao, 2000; Hinds, 1999). The single droplet collection efficiency due to this type of mechanism can be calculated by the following expressions (Licht, 1988):

(a) for potential flow around sphere

$$\eta_{DI} = 3 \frac{d_p}{d_d} \quad \text{for } \frac{d_p}{d_d} < 0.1 \quad (6.1)$$

(b) for viscous flow around a sphere

$$\eta_{DI} = \frac{3}{2} \left(\frac{d_p}{d_d} \right)^2 \quad \text{for } \frac{d_p}{d_d} < 0.1 \quad (6.2)$$

Inertial impaction. Inertial impaction occurs when the particle would miss the droplet if it follows the streamline, but its inertia resists the change in direction taken by the gas molecules

and it continues in a direct enough course to be collected by the droplet (Xiao, 2000; Hinds, 1999). The single droplet collection efficiency due to this type of mechanism can be calculated by the following expressions (Licht, 1988):

(a) for $0.416 \leq Stk \leq 0.30$

$$\eta_{IT} = 0.00376 - 0.464Stk + 9.68Stk^2 - 16.2Stk^3 \quad (6.3)$$

(b) for $Stk > 0.30$

$$\eta_{IT} = \frac{Stk^2}{(Stk + 0.25)^2} \quad (6.4)$$

where Stk is the Stokes number and is calculated using:

$$Stk = \frac{\rho_p d_p^2 C_c U_o}{18\mu d_d} \quad (6.6)$$

Gravitational settling. Gravitational settling is due to the difference in mass of the aerosol and the carrier gas. The collection efficiency due to this type of mechanism can be calculated by (Licht, 1988):

$$\eta_G = K_G = g \cdot Stk = \frac{C_c d_p^2 \rho_p}{18\mu U_o} g \quad (6.6)$$

Nielsen and Hill (1976a) developed another expression to calculate η_G for particles $>10\mu\text{m}$

$$\eta_G = \frac{K_G}{1 + K_G} \quad (6.7)$$

Otherwise it will be negligible for particles smaller than $10 \mu\text{m}$.

Brownian diffusion. Brownian deposition occurs as the particles are bombarded with gas molecules that may cause enough movement to permit the particle to come in contact with

the droplet. Brownian motion may also cause some of the particles to miss the droplet because they are moved away from it as they pass by (Xiao, 2000). The single droplet collection efficiency due to this type of mechanism can be calculated by the expression (Licht, 1988):

$$\eta_{BD} = \frac{\delta}{Pe^{0.5}} \quad (6.9)$$

where $\delta = 2.83$ (Stairmand, 1950) or 3.19 (Natanson, 1957) and Pe is the Peclet number, which is given by:

$$Pe = \frac{d_p U_o}{D} \quad (6.10)$$

The diffusivity, D , can be estimated by:

$$D = \frac{kTC_c}{3\pi\mu d_p} \quad (6.11)$$

In equation 6.11, k is the Boltzmann constant (1.38×10^{-23} N.m/K) and T is the absolute temperature, K.

Electrostatic deposition. Electrostatic attraction occurs because the particle, the droplet, or both possess sufficient electrical charge to overcome the inertial forces; the particle is then collected instead of passing the droplet. If a droplet is purposely charged by an applied electric field, the charge on the droplet will be larger than the random ions on it, then for some droplet sizes the electrostatic attraction is the dominant mechanism for particle removal. If only the droplets are charged, there is still improved collection of particles because of dipole forces. When the particles and/or the droplets are charged, there are five possible different electrostatic forces of attraction (Ranz and Wong, 1952; Licht, 1988):

(1) The Coulomb attraction between a charged particle and an oppositely charged collector (F_{EC}) (Licht, 1988):

$$F_{Ec} = \frac{q_d q_p}{4\pi r^2 \epsilon_o} \quad (6.12)$$

(2) The dipole attraction between the charged particle and the dipole that this charge induces on the neutral collector (F_{EM}) (Licht, 1988):

$$F_{EM} = \frac{q_p^2 d_d}{8\pi \epsilon_o r^3} - \frac{2q_p^2 d_d r}{\pi \epsilon_o (4r^2 - d_d^2)^2} \quad (6.13)$$

(3) The dipole attraction between the charged collector and the dipole induced upon the neutral particle (F_{EI}) (Licht, 1988):

$$F_{EI} = -\left(\frac{\epsilon - 1}{\epsilon + 2}\right) - \frac{d_p^2 q_d^2}{16\pi \epsilon_o r^5} \quad (6.14)$$

(4) The space charge repulsion of the cloud of charged particles (F_{ES}):

$$F_{ES} = \frac{-q_p d_d E}{24 \epsilon_o r^2} \quad (6.15)$$

The electrostatic repulsive force between two point charges of like sign separated by a distance r is given by Coulomb's law (Hinds, 1999):

$$F_E = K_E \frac{qq'}{r^2} \quad (6.16)$$

$$K_E = \frac{1}{4\pi \epsilon_o} = 9.0 \times 10^9 \frac{N \cdot m^2}{C} \quad (6.17)$$

(5) The attraction between the charged particle and the earthed collector, which carries an image charge, induced by the space charge of the surrounding aerosol.

If an electric field is applied so that the droplet, although uncharged, is polarized, two more forces must be considered: (1) the force of attraction due to the distortion of the electric field by the presence of the particle and (2) the dipole attraction owing to the interaction between the dipole induced on the aerosol particle by the applied field and the non-uniform electric field in the vicinity of the collector. This is called the dielectrophoretic effect (Licht, 1988, Xiao, 2000)

The analysis of the effect of these forces, together with other mechanisms, upon aerodynamic capture of particles is complicated. In principle, the appropriate electrostatic forces should be added, that is,

$$F_E = F_{EM} + F_{EI} + F_{EC} + F_{ES} \quad (6.18)$$

The removal efficiencies associated with these forces are summarized in Table 6-1. The resultant effect of these forces will control the collection efficiency of particles by the collector. One or more of these forces will be the dominant force that controls the collection efficiency. Factors that can influence particle collection associated with these forces are summarized in Table 6-2. The effects on the other collection mechanisms are also listed in Table 6-2.

Table 6-1 Equations describing the removal efficiencies due to different electrostatic forces

Type of Force	Collector	Particle	Parameter Z	Efficiency	
EM*	Charged	Neutral	$Z_{Em} = \frac{C_c q_p^2}{3\pi^2 d_p \mu_a U_o \epsilon_o d_d^2}$	$\eta = 1.58 Z_{Em}^{0.5}$	for potential flow $0.002 \leq Z_{Em} \leq 0.1$
				$\eta = 2.89 Z_{Em}^{0.353}$	for viscous flow
EI*	Neutral	Charged	$Z_{EI} = \left(\frac{\epsilon_r - 1}{\epsilon_r + 2}\right) \frac{2C_c d_p^2 q_d^2}{3\pi \mu_a d_d U_o \epsilon_o}$	$\eta = \left(\frac{15\pi}{8} Z_{EI}\right)^{0.4}$	
EC*	Charged	Charged	$Z_E = \frac{2C_c q_p q_d}{3\pi d_p \mu_a U_o \epsilon_o}$	$\eta = -4Z_E$	for potential and viscous flow
	Opposite				
ES [§]	Charged	Charged	$Z_{ex} = \frac{C_c q_p E}{6\pi r_p \mu_o U_o}$	$\eta = -\frac{4Z_E}{1 + Z_{ex}}$	
	Similar				

* Source: Licht (1988)

§ Source: Nielsen and Hill (1976a)

Table 6-2 Effect of different parameters on the collection efficiency for each mechanism (Licht, 1988).

Mechanism		Trends on Efficiency η^a		
		d_p (Increase)	d_d (Increase)	U_o (Increase)
Direct Interception		up	down	-
Inertial Impaction		up	down	up
Gravitational Settling		up	-	down
Brownian Deposition		down	down	down
Electrostatic	EM	down	down	down
	EI	up	down	down
	EC	down	down	down
	ES	down	up	down

^aTrend means effect on η as variable is increased

6.3.2 Coagulation

Coagulation of aerosols is a process in which aerosol particles collide with one another, due to a relative motion between them and adhere to form larger particles. The net result is a continuous decrease in number concentration coupled with an increase in particle size (Hinds, 1999). Coagulation may be classified as either Brownian coagulation or kinematic coagulation, depending on the cause (Brownian, mechanical and electrostatic forces) for the relative motion between the particles and droplet. Brownian coagulation can be described using:

$$N_{(t)} = \frac{N_o}{1 + N_o K t} \quad (6.19)$$

where $N_{(t)}$ is the number concentration after time t , N_o is the initial concentration, and K is the coagulation coefficient, that is,

$$K = K_o B \quad (6.20)$$

In equation 6.20, B is the coagulation correction factor that depends on the collection mechanisms like the mechanical and electrostatic forces, and K_o can be calculated using the following expressions:

(1) for monodisperse particles

$$K_o = 4\pi d_p D \quad (6.21)$$

(2) for polydisperse particles or for droplets with particles

$$K_o = K_{pd} = \pi(d_p + d_d)(D_p + D_d) \quad (6.22)$$

The rate of capture of small particles by a water droplet due to kinematic coagulation is given by:

$$n_c = \frac{\pi}{4} d_d^2 V_{TS} NE \quad (6.23)$$

where N is number concentration of particles, V_{TS} is the settling velocity of the droplet, and E is capture efficiency, which can be determined using:

$$E = \left(\frac{Stk}{Stk + 0.12} \right)^2 \quad \text{for } Stk \geq 0.1 \quad (6.24)$$

6.4 Collection of Dust Particles by Charged Water Spray

To simplify the analysis of the collection process of aerosol particles by water droplets, the coagulation process between the particles with each other and the particles with water droplets can be used. Xiang (1997) stated that due to the large specific surface area of aerosols, generally all contacts between particles will result in a coagulation process and the particles cannot separate from each other, and most aerosol particles carry some electric charge with the effect on coagulation depending on the sign of their charges. A coagulation model could give a good estimation of the reduction in dust particles taking to account enhancement of particle collection due to electrostatic forces.

If equation 6.19 is used, since the parameters N_o and t are known values, the key step is to estimate the value of K_{dp} . Note that the coagulation of polydisperse particles is a complicated process compared with monodisperse particles. To simplify, initially the case between each particle size range for size scale (0.54-20 μm) and water droplets (approximately 20 μm in diameter) will be considered. The Brownian coagulation between each particle size range and water droplet could be computed using equation 6.22. However, such approach will severely underestimate K_{dp} because the calculated K_{dp} would only account for the coagulation between the water droplets and particles due to the Brownian motion. The other mechanisms, such as kinematic coagulation and enhancement of coagulation because of electrostatic forces, would not be considered.

6.4.1 Modified coagulation model

To account for the other mechanisms, for this study, the coagulation model was modified by using experimentally derived K values in place of the theoretical K values. Equation 6-19 can then be re-written as,

$$N_{(t)} = \frac{N_o}{1 + N_o K_{exp} t} \quad (6.25)$$

where K_{exp} is the experimental coagulation rate coefficient and could be related to K_{dp} using:

$$K_{exp} = K_{dp} \alpha \quad (6.26)$$

where α is the correction factor to account for the effects of mechanical forces (MF) and electrostatic forces (EF).

In terms of mass concentration, the modified coagulation model can be described using:

$$C_t = \frac{C_o}{1 + C_o K_{exp, m} t} \quad (6.27)$$

where C_o is the initial mass concentration at $t = 0$, C_t is the mass concentration after time t , and $K_{exp, m}$ is the mass-based experimental coagulation coefficient.

From the experimental data on corn starch in Chapter 5, the K_{exp} values were obtained as a function of aerodynamic diameter of the corn starch particles and time t , that is,

$$K_{exp} = \frac{\left[\frac{1}{N_t} - \frac{1}{N_o} \right]}{t} \quad (6.28)$$

Figure 6-2 summarizes the calculated K_{exp} values at $t=10$ min for the no-spray case (representing the combined effects of the Brownian and kinematic coagulation), for the uncharged water spray, and for the charged-water spray case (representing enhanced coagulation due to electrostatic forces and water spray). The K_{exp} values associated with the charged spray were considerably

larger than those for the no spray and uncharged water spray cases (Fig. 6-2). The Brownian coagulation coefficients (calculated using equation 6.22) ranged from 1.8×10^{-8} to 2.2×10^{-7} cm^3/min , and are several orders of magnitude smaller than the experimental values. Similar results were observed for NaHCO_3 (Figs. 6-4 and 6-5).

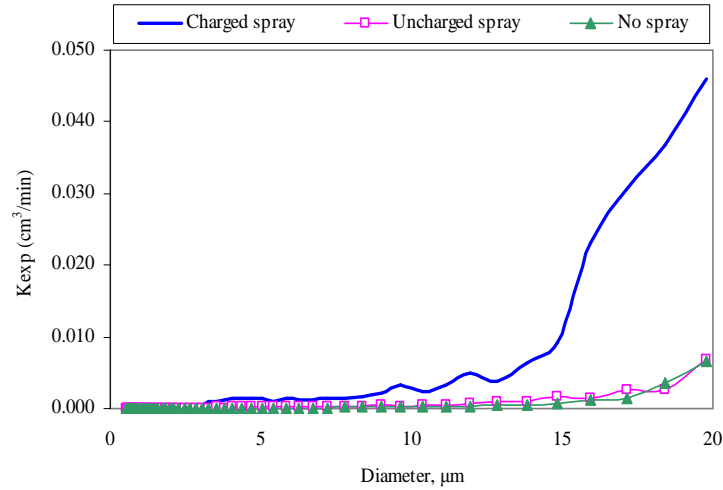


Figure 6-2 Values of K_{exp} for corn starch obtained from the experimental data (from APS).

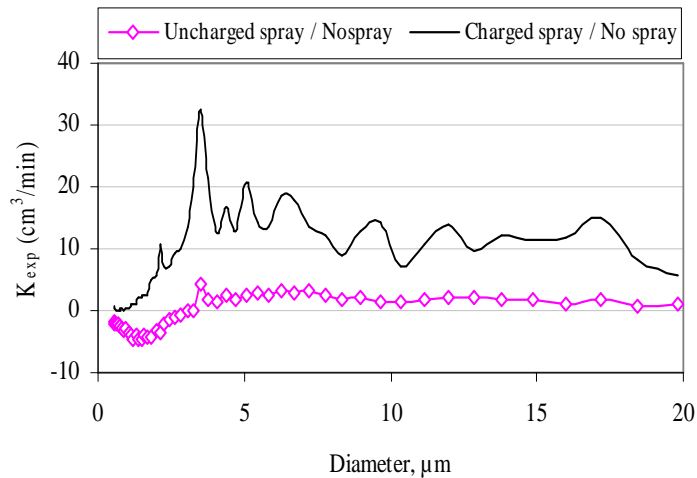


Figure 6-3 Value of K_{exp} as a ratio of charged water and uncharged water to no spray for corn starch obtained from the experimental data (from APS).

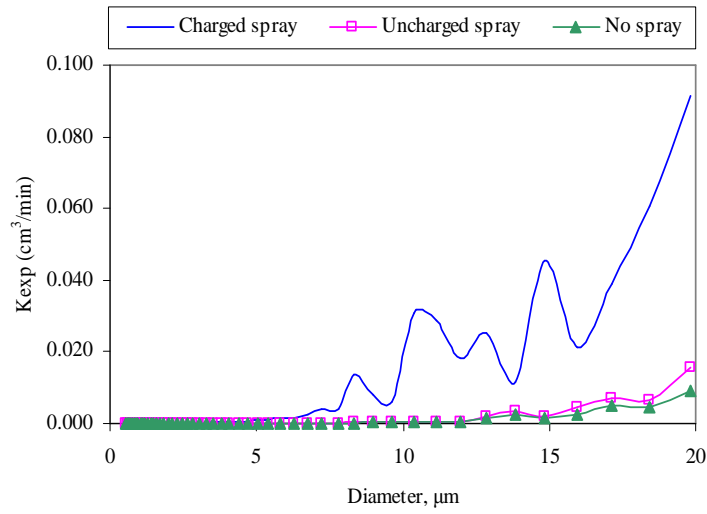


Figure 6-4 Values of K_{exp} for NaHCO_3 obtained from the experimental data (from APS).

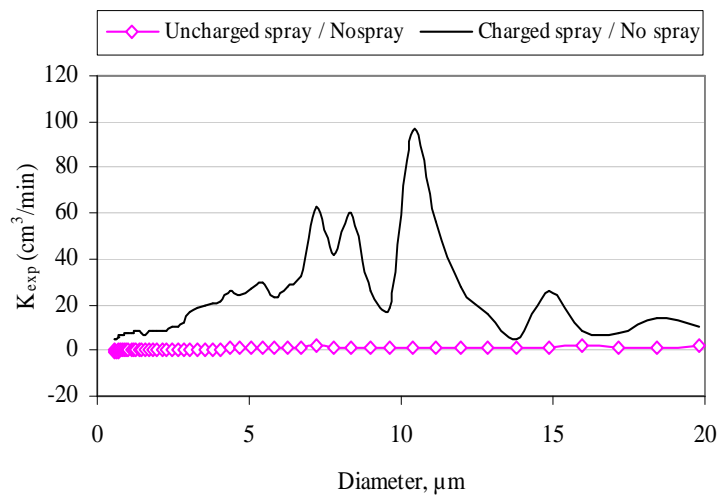


Figure 6-5 Value of K_{exp} as a ratio of charged water and uncharged water to no spray for NaHCO_3 obtained from the experimental data (from APS).

The data in the figures show that the electrostatic force greatly enhanced the coagulation process compared with uncharged water spray and no spray case. The degree of enhancement depends on many factors such as droplet and particle diameter, charge magnitude, and type of particles.

The model was also applied on the mass concentrations obtained from the TEOM (Fig. 6-6 and 6-7), that is, values of $K_{exp,m}$ were obtained using the equation:

$$K_{exp,m} = \frac{\frac{1}{C_o} - \frac{1}{C_t}}{t} \quad (6.29)$$

The calculated $K_{exp,m}$ values are summarized in Figures 6-8 and 6-9. Again, the $K_{exp,m}$ values were considerably larger for charged water spray than for the uncharged water spray or no spray cases.

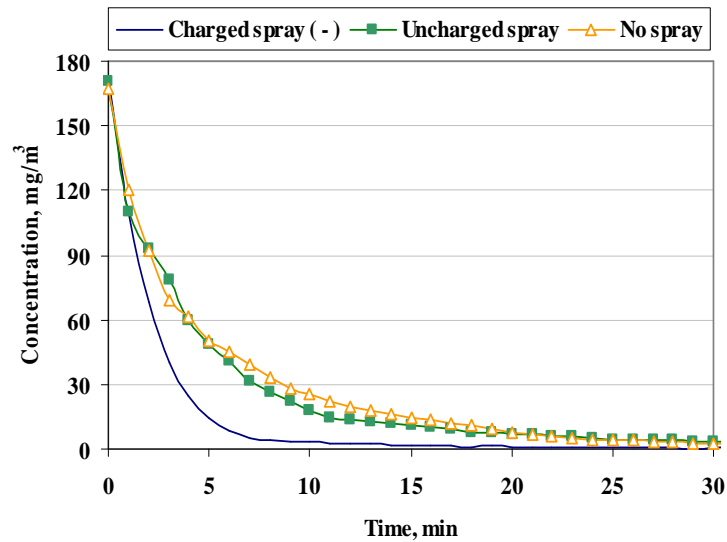


Figure 6-6 Reduction in corn starch particle mass concentration using charged water spray, uncharged spray, and no spray.

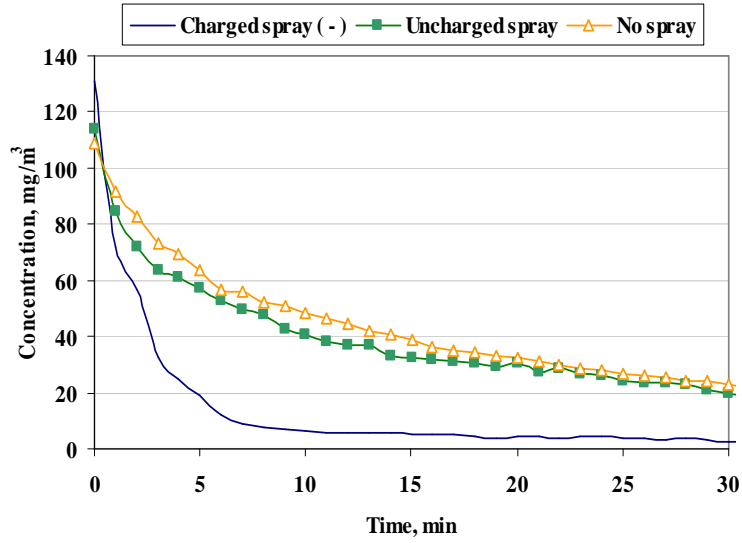


Figure 6-7 Reduction in NaHCO₃ particle mass concentration using charged water spray, uncharged spray, and no spray.

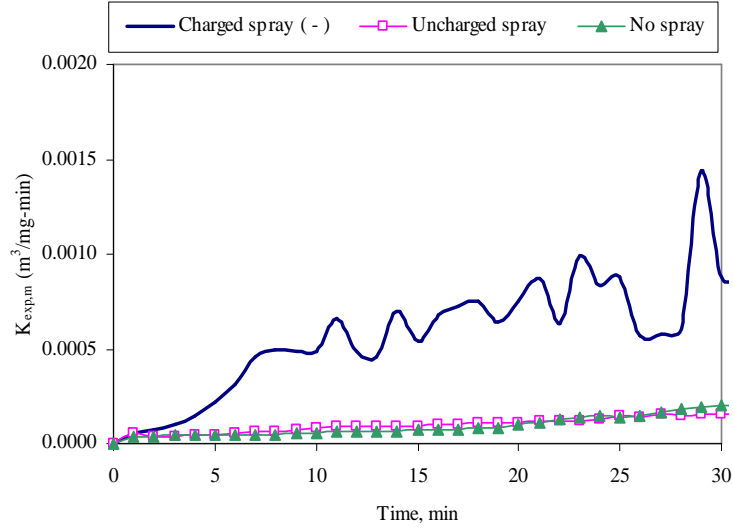


Figure 6-8 Value of $K_{exp,m}$ for corn starch obtained from the experimental TEOM data.

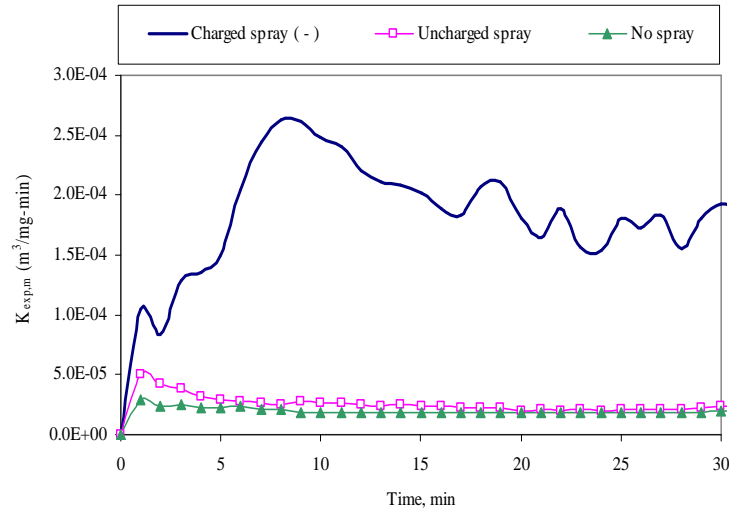


Figure 6-9 Values of $K_{exp,m}$ for NaHCO_3 obtained from the experimental TEOM data.

6.4.2 Comparison of predicted and measured values

To verify the modified coagulation model, predicted values were compared with measured values. Additional sets of experiments were conducted on corn starch and NaHCO_3 . From the experimental data from these additional experiments, the number and mass concentrations were calculated using equations 6.25 and 6.27, respectively, and applying the K_{exp} and $K_{exp,m}$ values presented above. In addition, the removal efficiencies were calculated based on the following equation:

$$\eta_{predicted} = 1 - \left(\frac{1}{1 + N_o \cdot K_{exp} \cdot t} \right) \quad (6.30)$$

Figures 6-10 to 6-21 show the measured and predicted particle number concentrations and removal efficiencies using charged water spray and for the no spray case for corn starch and NaHCO_3 . In general, predicted values agreed well with measured data.

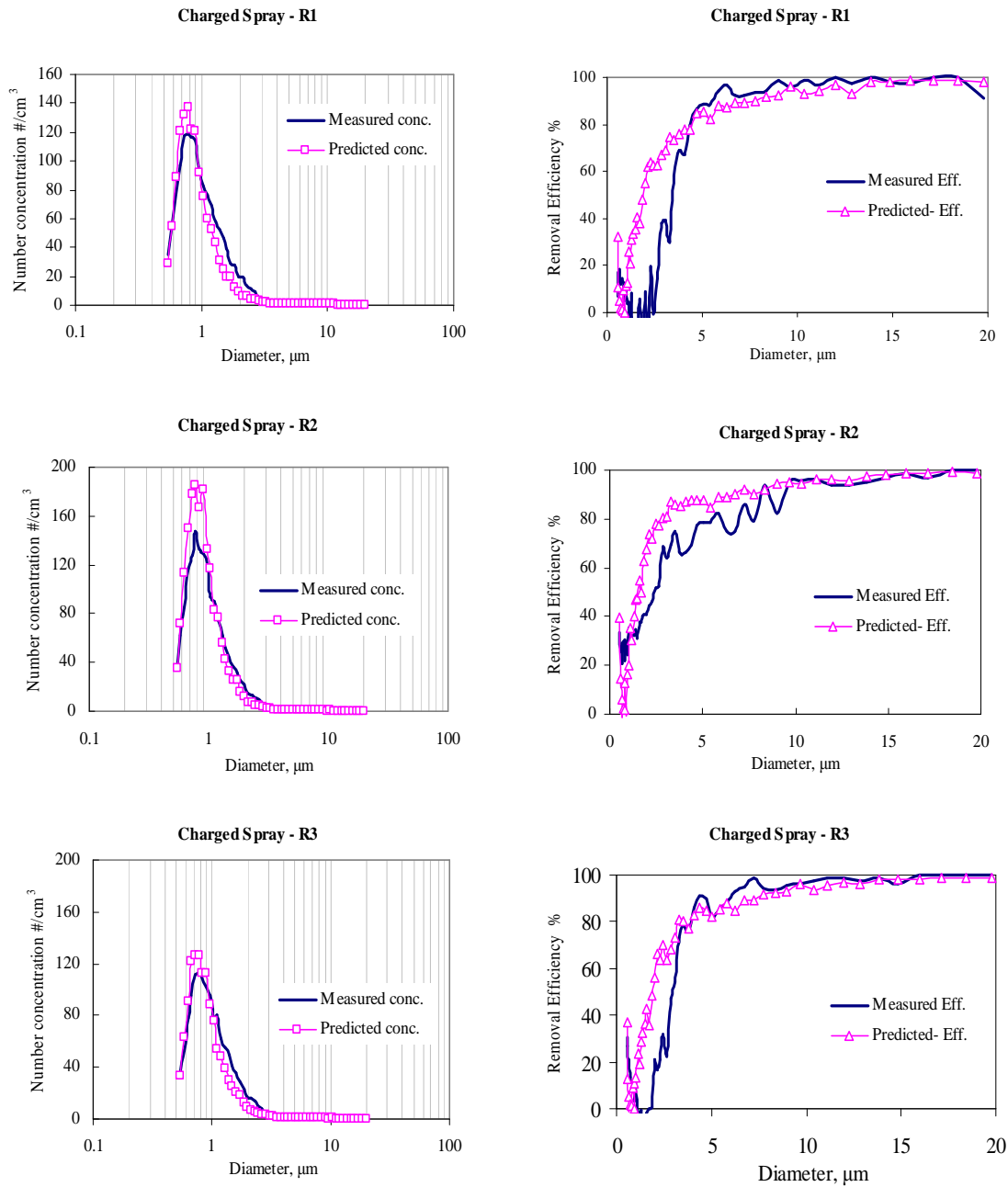


Figure 6-10 Measured and predicted values of number concentrations and removal efficiencies at $t=10$ min for corn starch using negatively charged water spray. Data were obtained by the Aerodynamic Particle Sizer (APS) spectrometer.

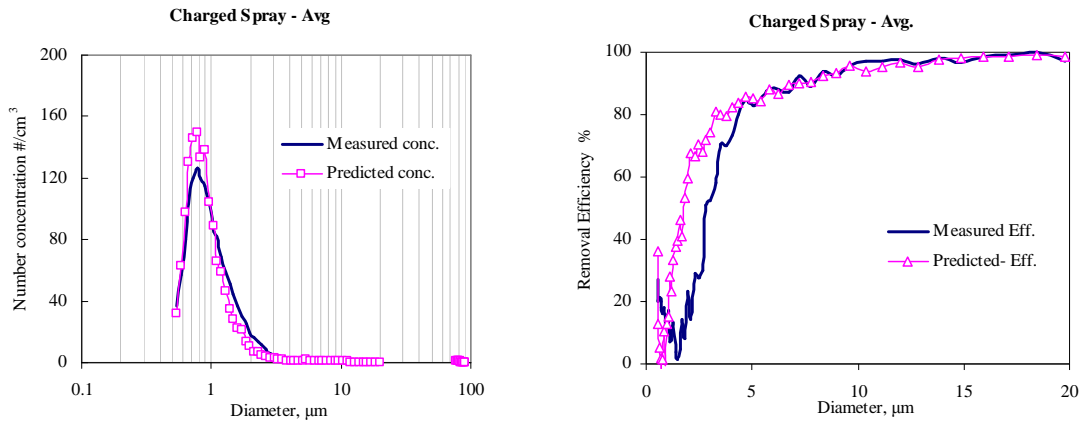


Figure 6-11 Average of measured and predicted values of number concentration and removal efficiency at $t=10$ min for corn starch using negatively charged water spray. Data were obtained by the Aerodynamic Particle Sizer (APS) spectrometer.

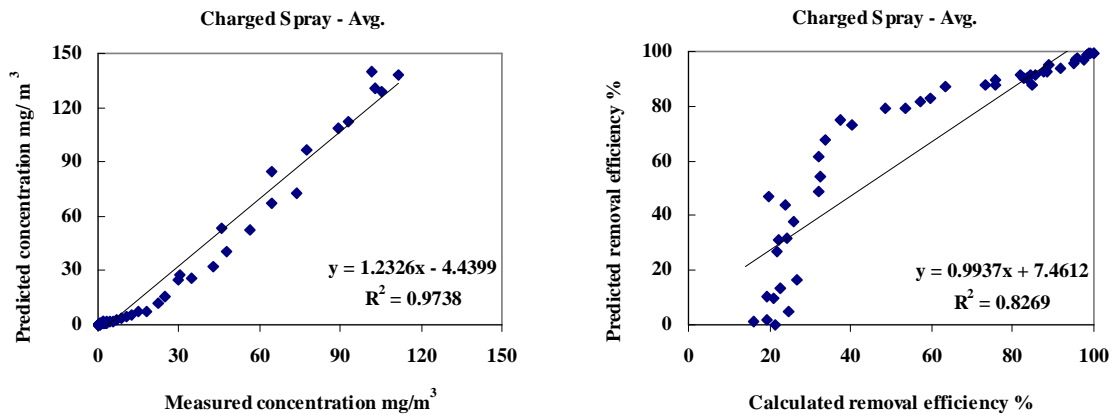


Figure 6-12 Correlation between measured and predicted values of mass concentration and removal efficiency at $t=10$ min for corn starch using negatively charged water spray.

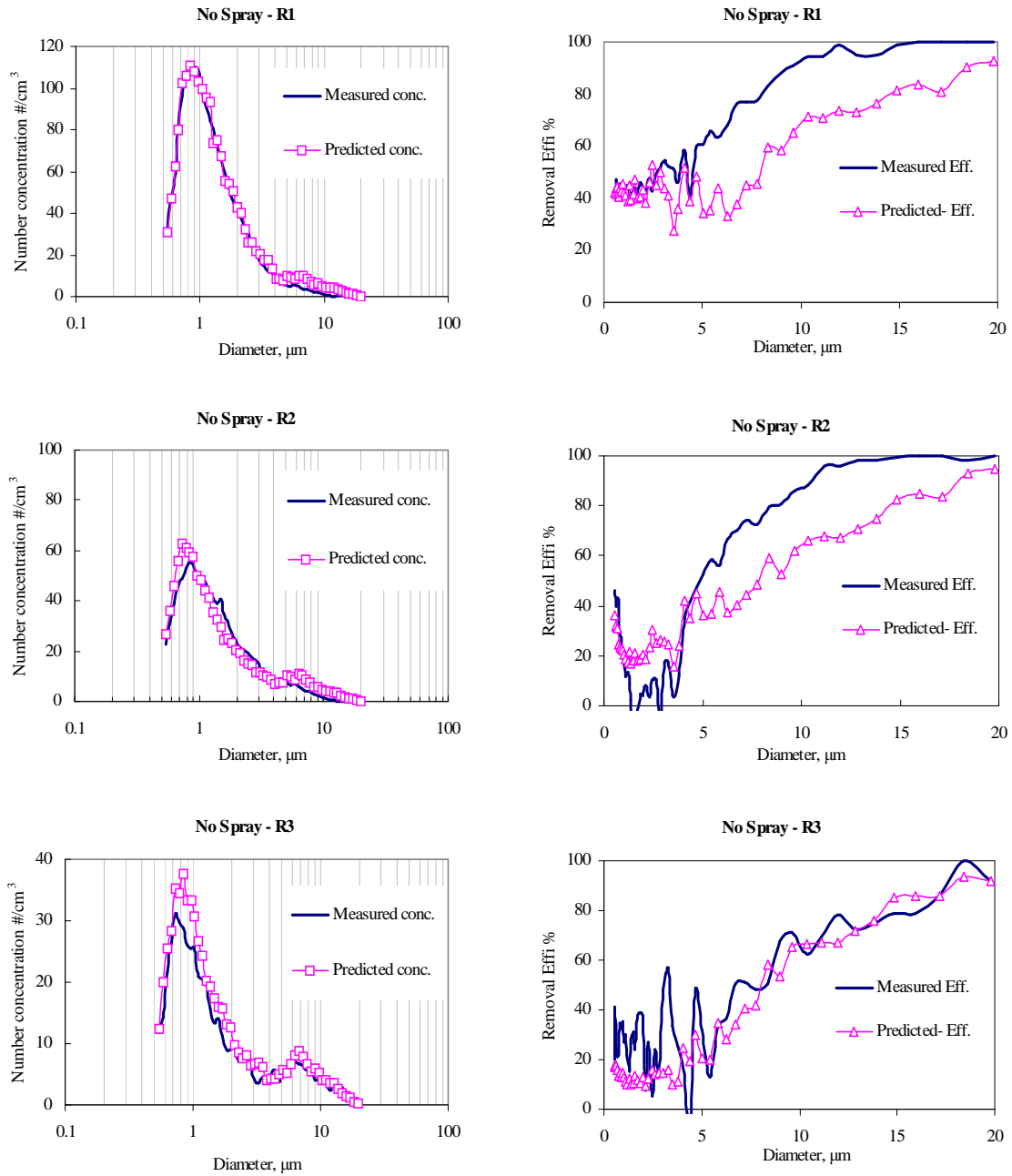


Figure 6-13 Measured and predicted values of number concentrations and removal efficiencies at $t=10$ min for corn starch using no spray. Data were obtained by the Aerodynamic Particle Sizer (APS) spectrometer.

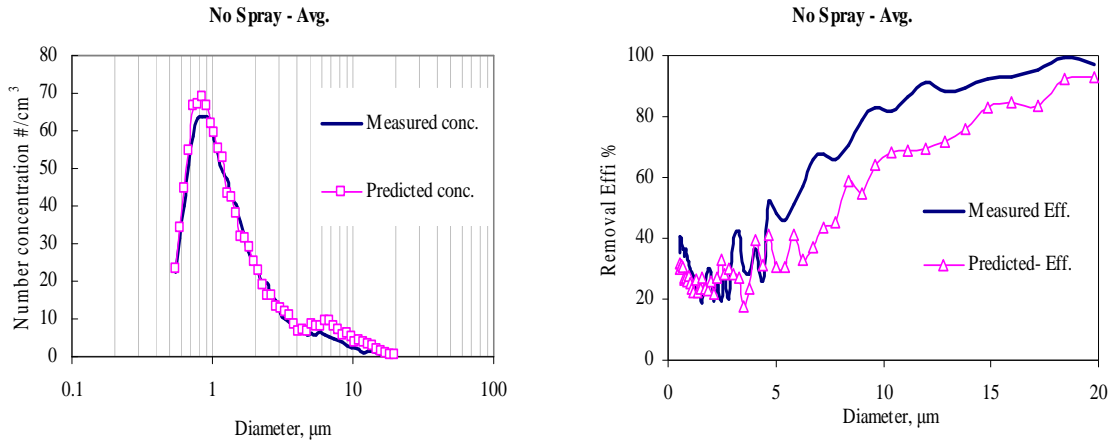


Figure 6-14 Average of measured and predicted values of number concentration and removal efficiency at $t=10$ min for corn starch using no spray. Data were obtained by the Aerodynamic Particle Sizer (APS) spectrometer.

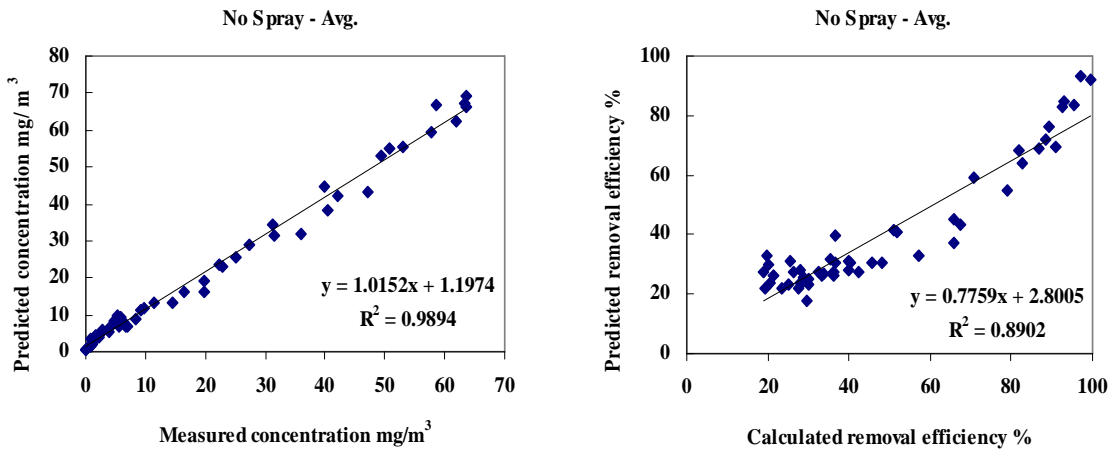


Figure 6-15 Correlation between measured and predicted values of mass concentration and removal efficiency at $t=10$ min for corn starch using no water spray.

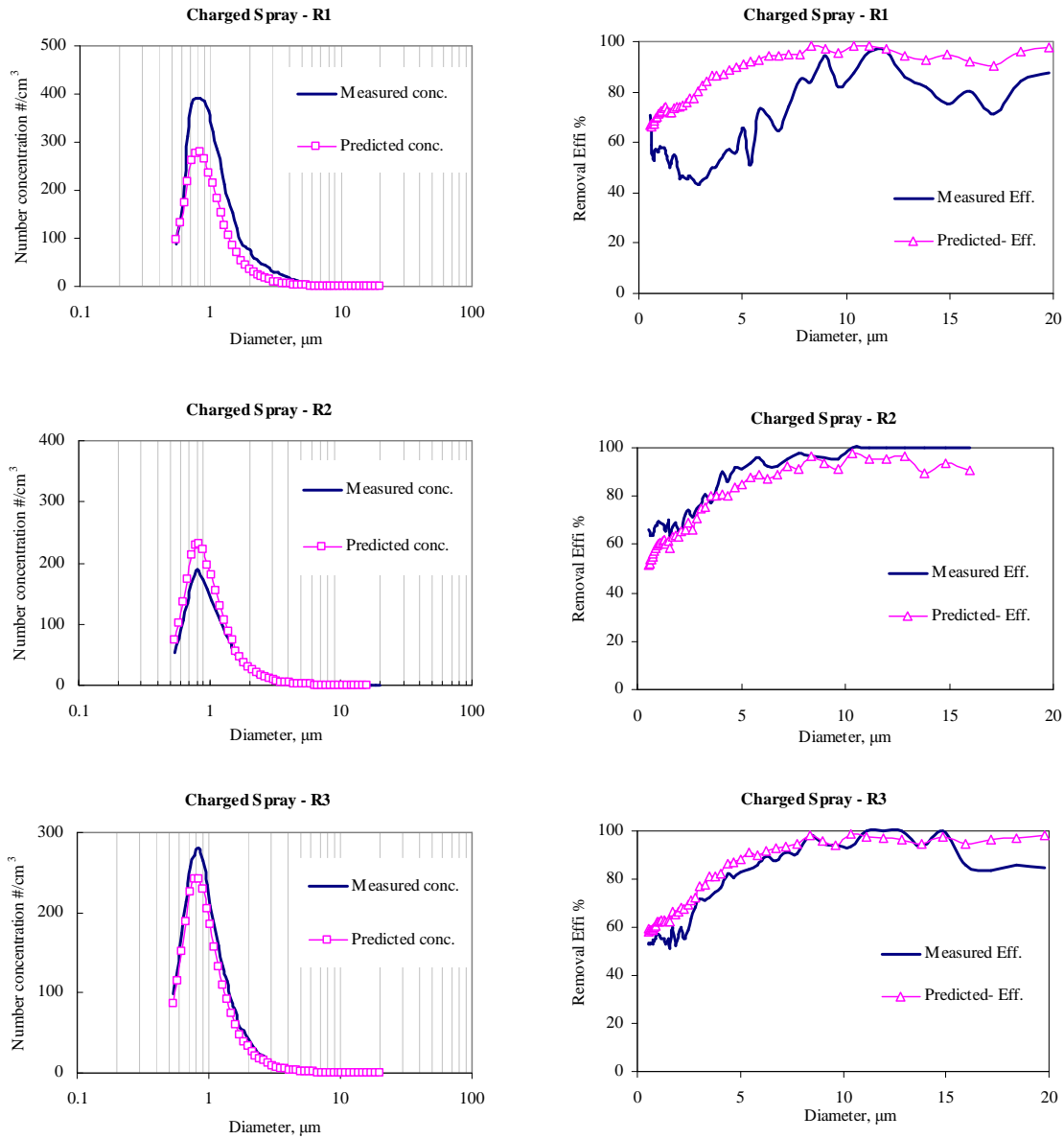


Figure 6-16 Measured and predicted values of number concentration and removal efficiency at $t=10$ min for NaHCO_3 using negatively charged water spray. Data were obtained by the Aerodynamic Particle Sizer (APS) spectrometer.

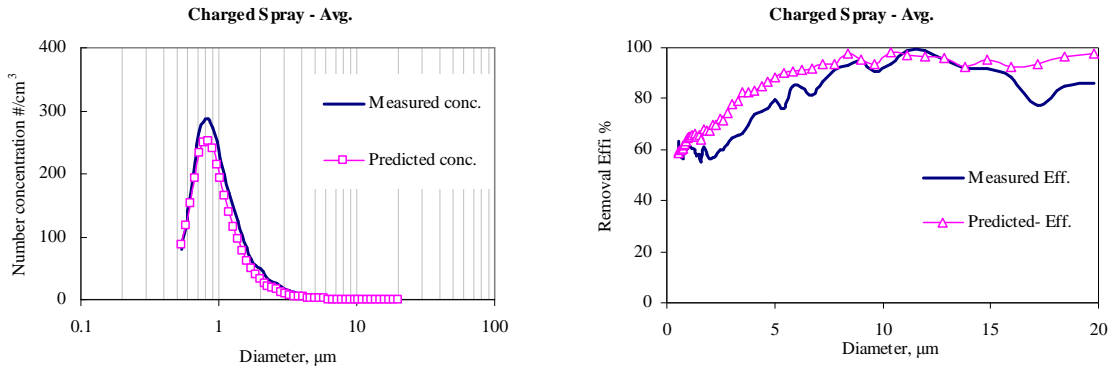


Figure 6-17 Average of measured and predicted values of number concentration and removal efficiency at $t=10$ min for NaHCO_3 using negatively charged water spray. Data were obtained by the Aerodynamic Particle Sizer (APS) spectrometer.

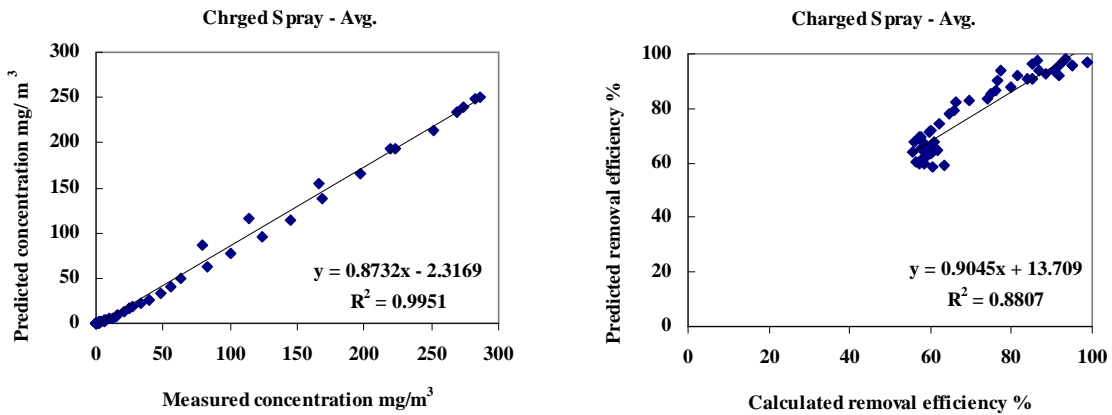


Figure 6-18 Correlation between measured and predicted values of mass concentration and removal efficiency at $t=10$ min for NaHCO_3 using negatively charged water spray.

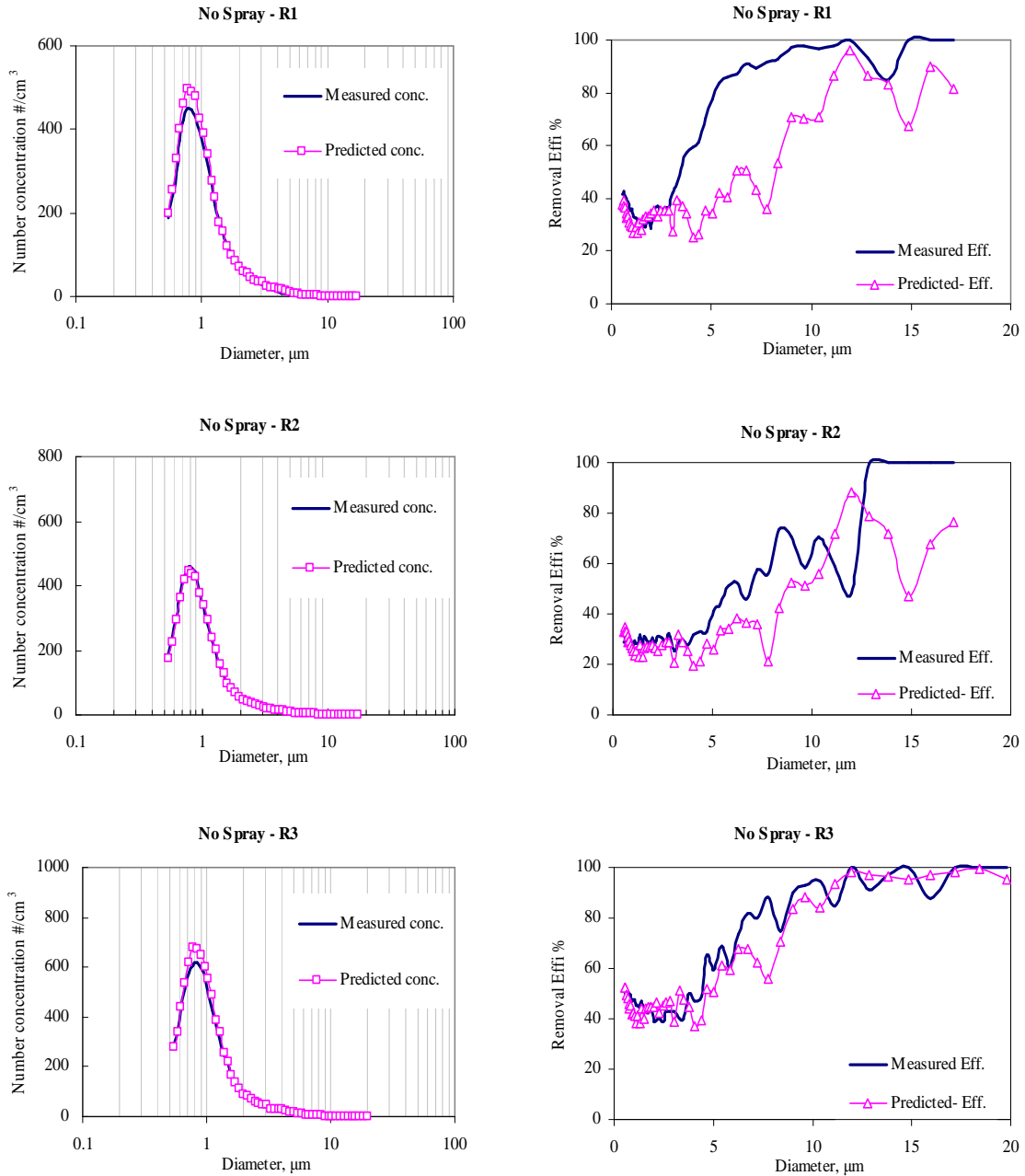


Figure 6-19 Measured and predicted values of number concentration and removal efficiency at $t=10$ min for NaHCO_3 for the no spray case. Data were obtained by the Aerodynamic Particle Sizer (APS) spectrometer.

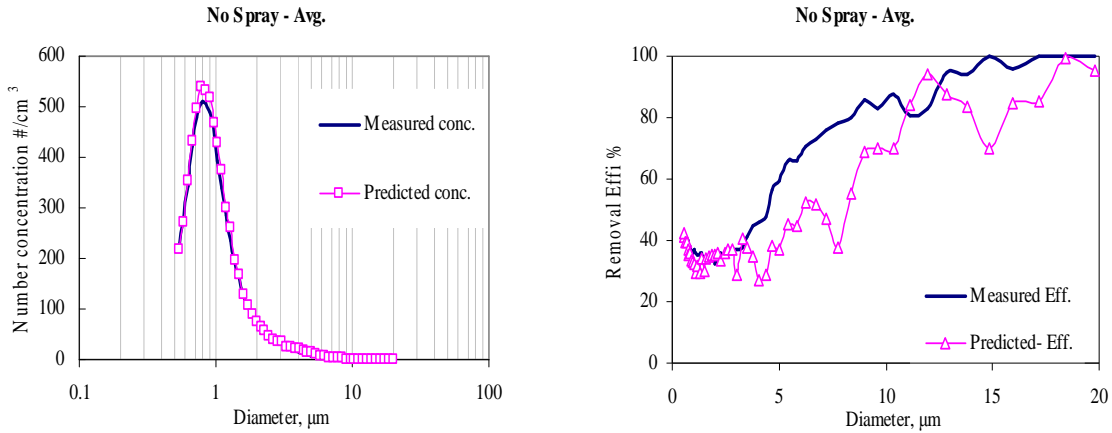


Figure 6-20 Average of measured and predicted values of number concentration and removal efficiency at $t=10$ min for NaHCO_3 for the no spray case. Data were obtained by the Aerodynamic Particle Sizer (APS) spectrometer.

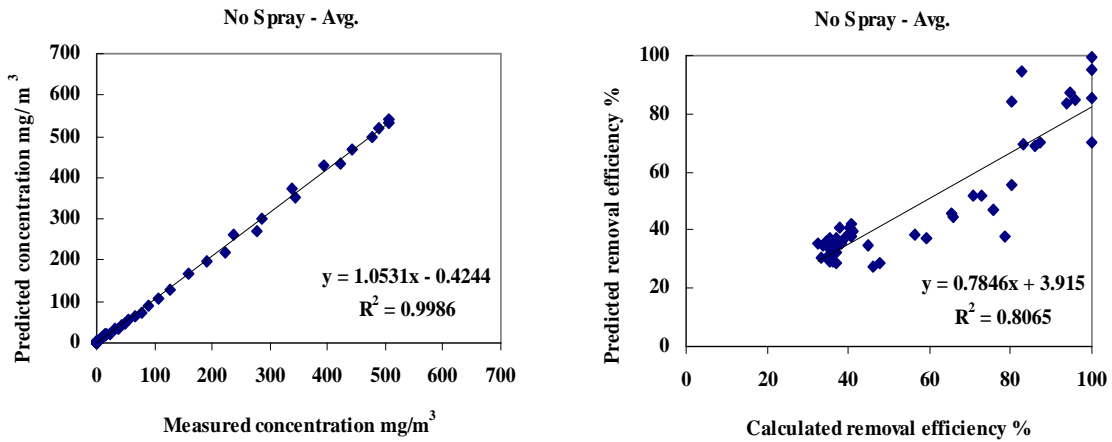


Figure 6-21 Correlation between measured and predicted values of mass concentration and removal efficiency at $t=10$ min for NaHCO_3 using no water spray.

Figures 6-22 to 6-33 show the measured and predicted particle mass concentrations and removal efficiencies for the charged water spray and no spray cases for corn starch and NaHCO_3 . Again, predicted values agreed well with measured values.

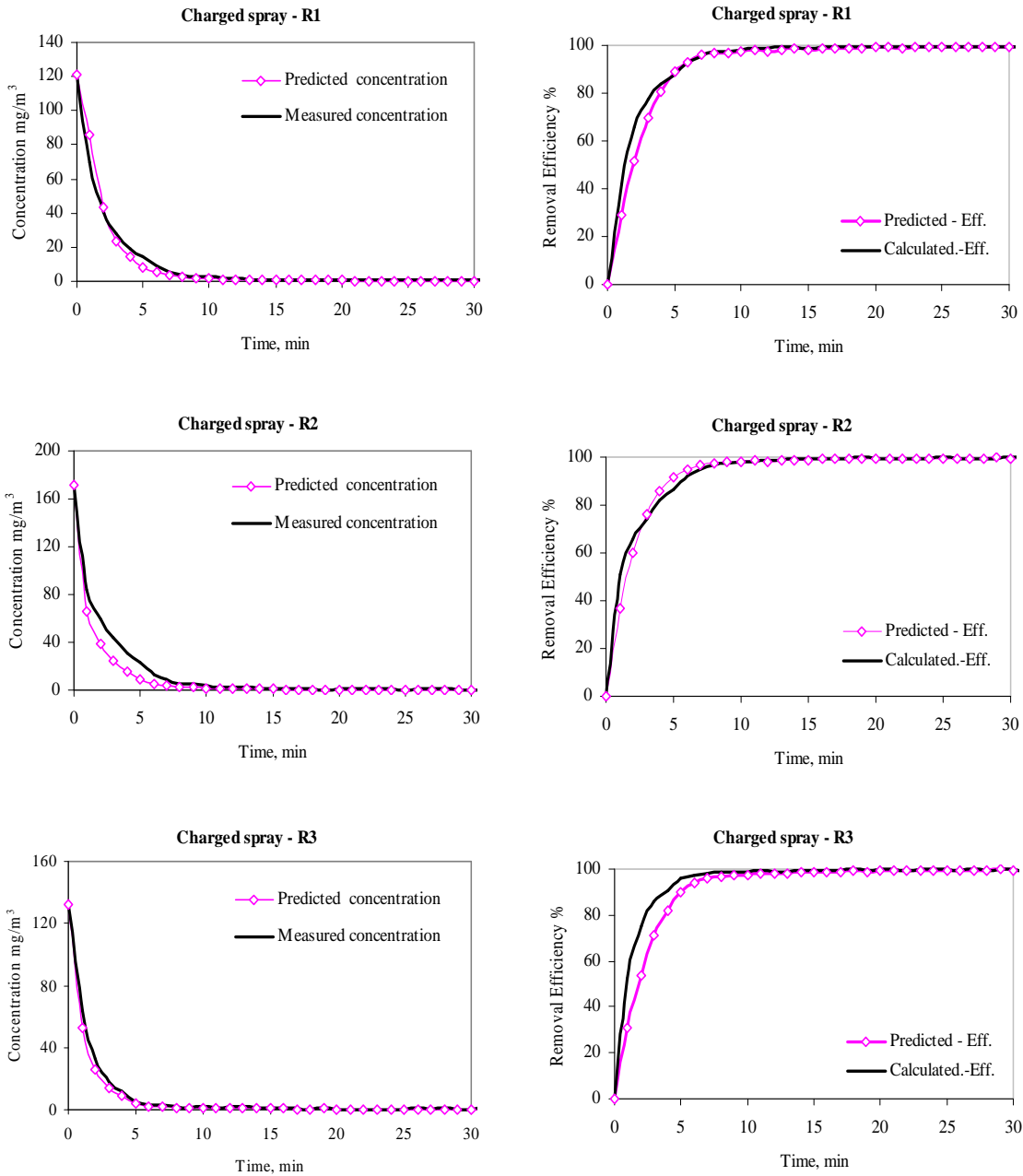


Figure 6-22 Measured and predicted values of mass concentration and removal efficiency for corn starch using negatively charged water spray. Data were obtained by the Tapered Element Oscillating Microbalance (TEOM).

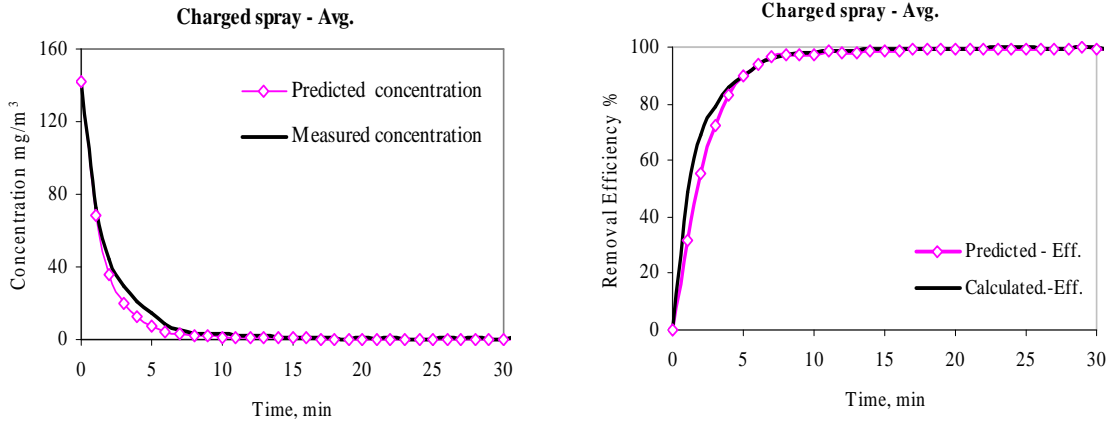


Figure 6-23 Average of measured and predicted values of mass concentration and removal efficiency for corn starch using negatively charged water spray. Data were obtained by the Tapered Element Oscillating Microbalance (TEOM).

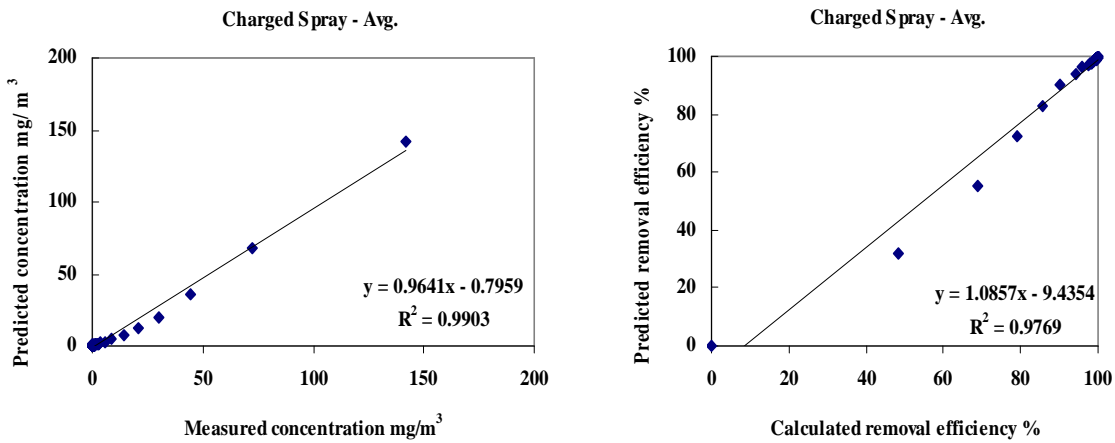


Figure 6-24 Correlation between measured and predicted values of mass concentration and removal efficiency at $t=10$ min for corn starch using negatively charged water spray.

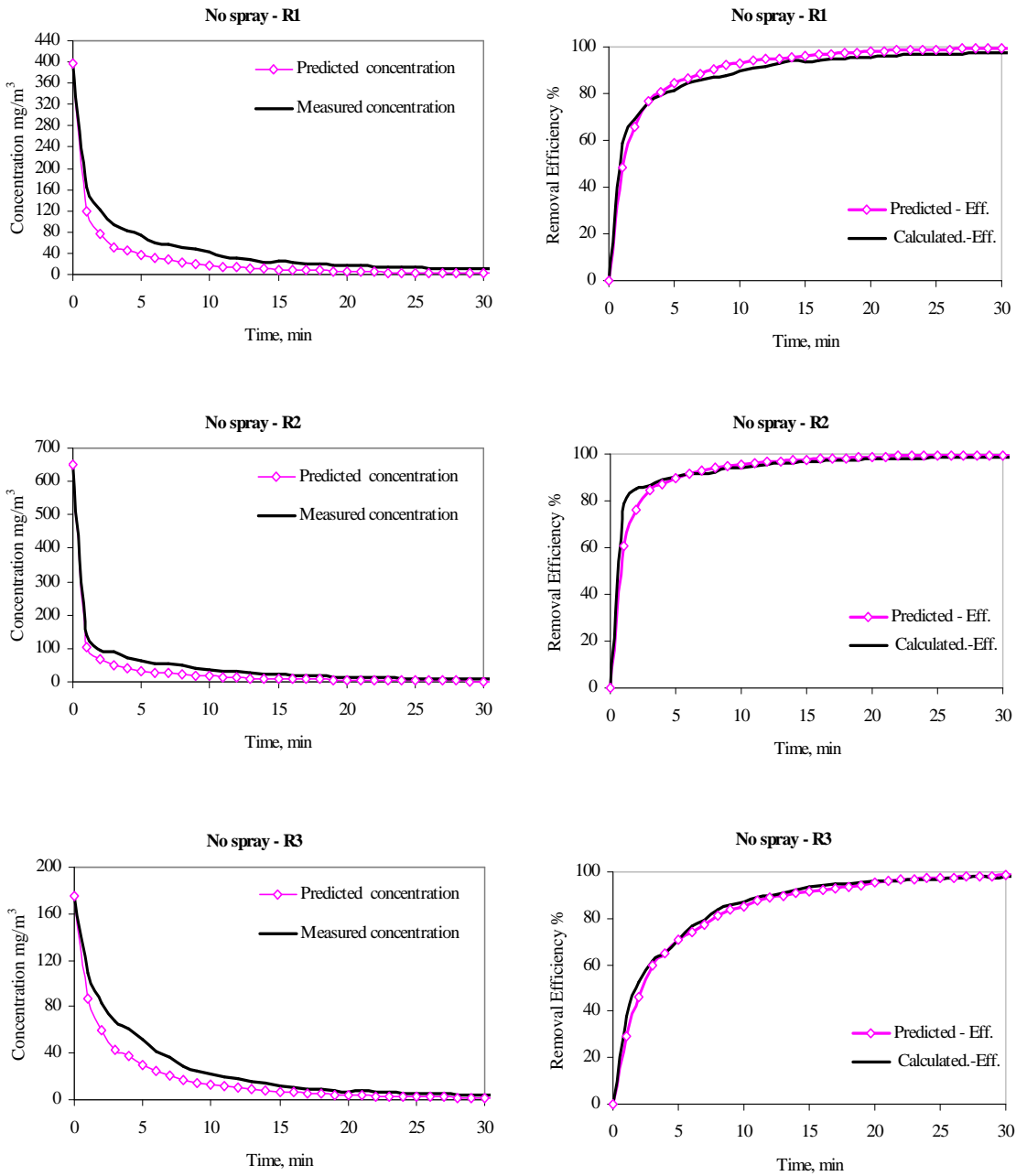


Figure 6-25 Measured and predicted values of mass concentration and removal efficiency for corn starch for the no spray case. Data were obtained by the Tapered Element Oscillating Microbalance (TEOM).

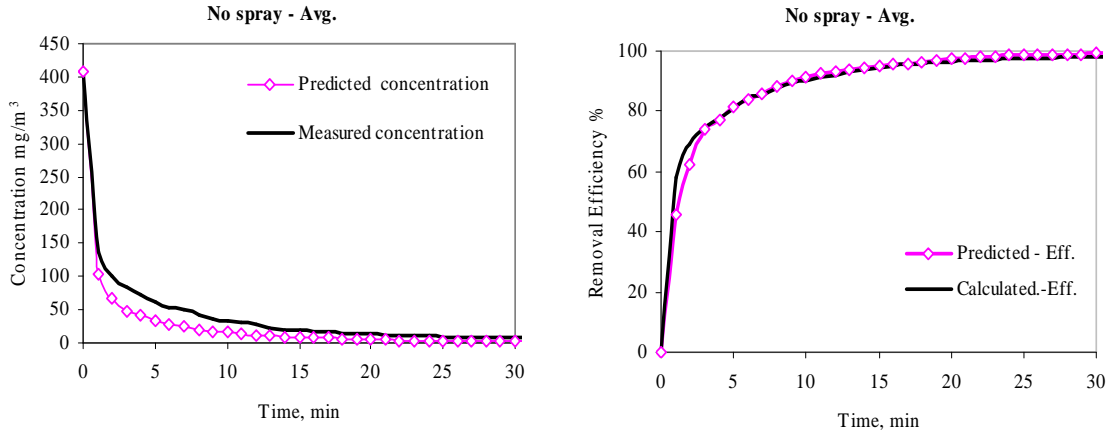


Figure 6-26 Average of measured and predicted values of mass concentration and removal efficiency for corn starch for the no spray case. Data were obtained by the Tapered Element Oscillating Microbalance (TEOM).

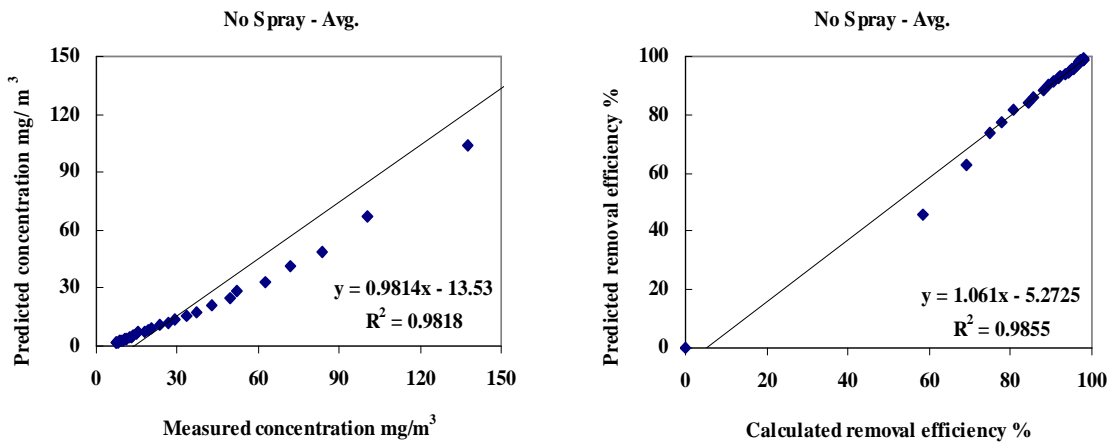


Figure 6-27 Correlation between measured and predicted values of mass concentration and removal efficiency at $t=10$ min for corn starch using no water spray.

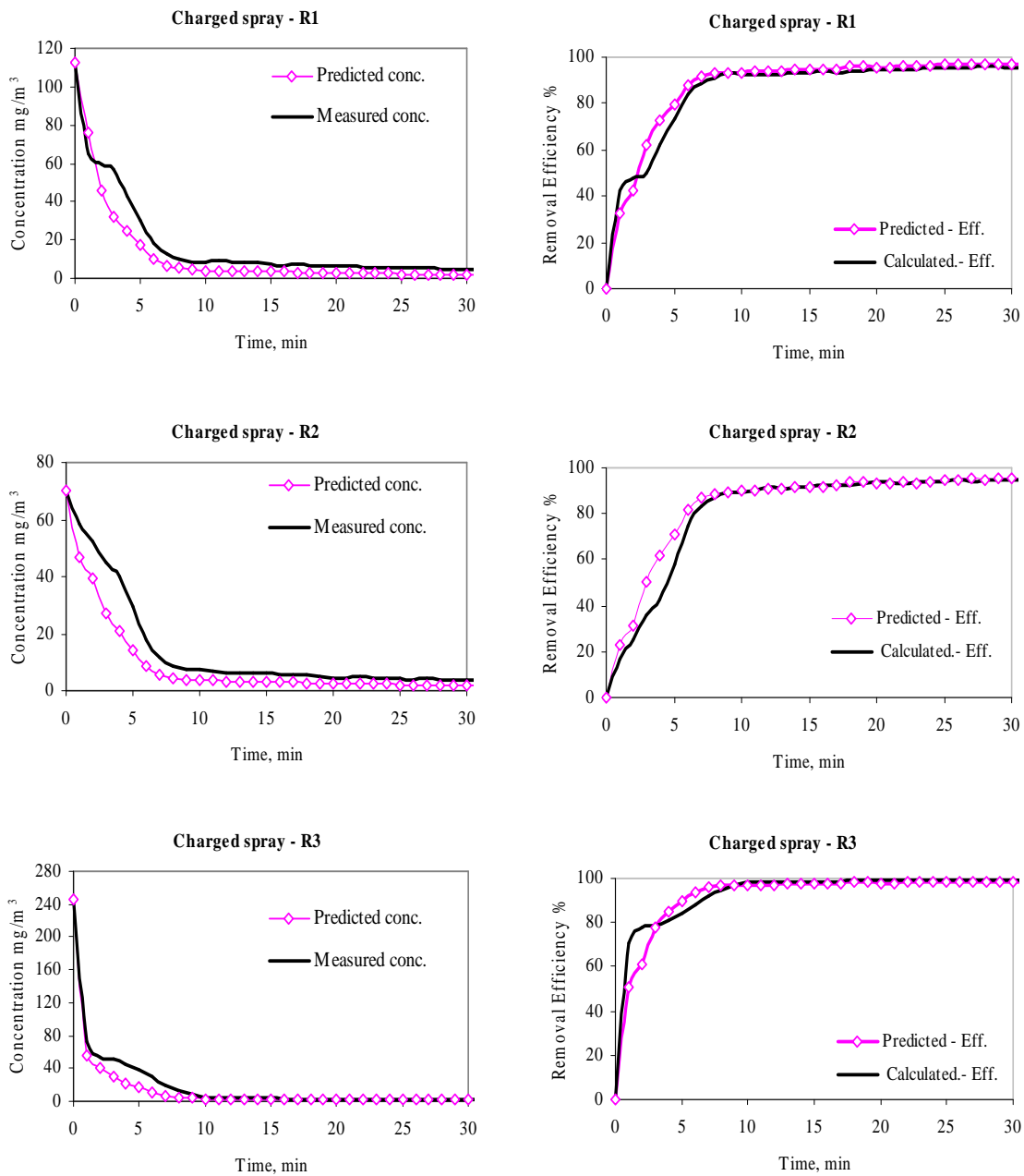


Figure 6-28 Measured and predicted values of mass concentration and removal efficiency for NaHCO₃ using negatively charged water spray. Data were obtained by the Tapered Element Oscillating Microbalance (TEOM).

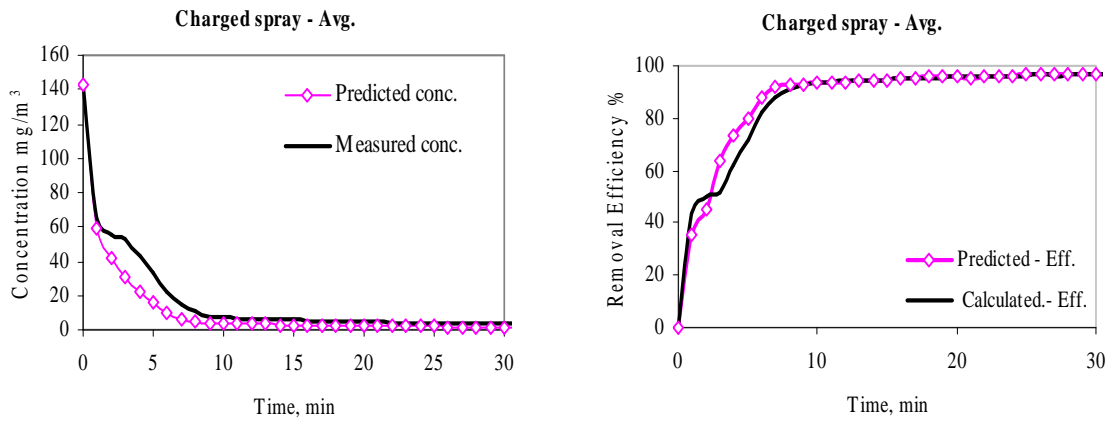


Figure 6-29 Average of measured and predicted values of mass concentration and removal efficiency for NaHCO_3 using negatively charged water spray. Data were obtained by the Tapered Element Oscillating Microbalance (TEOM).

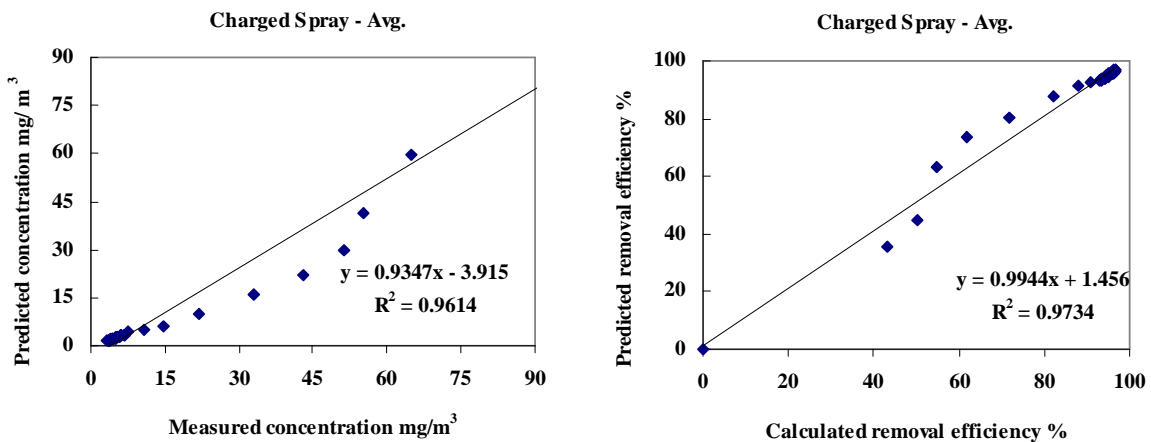


Figure 6-30 Correlation between measured and predicted values of mass concentration and removal efficiency at $t=10$ min for NaHCO_3 using negatively charged water spray.

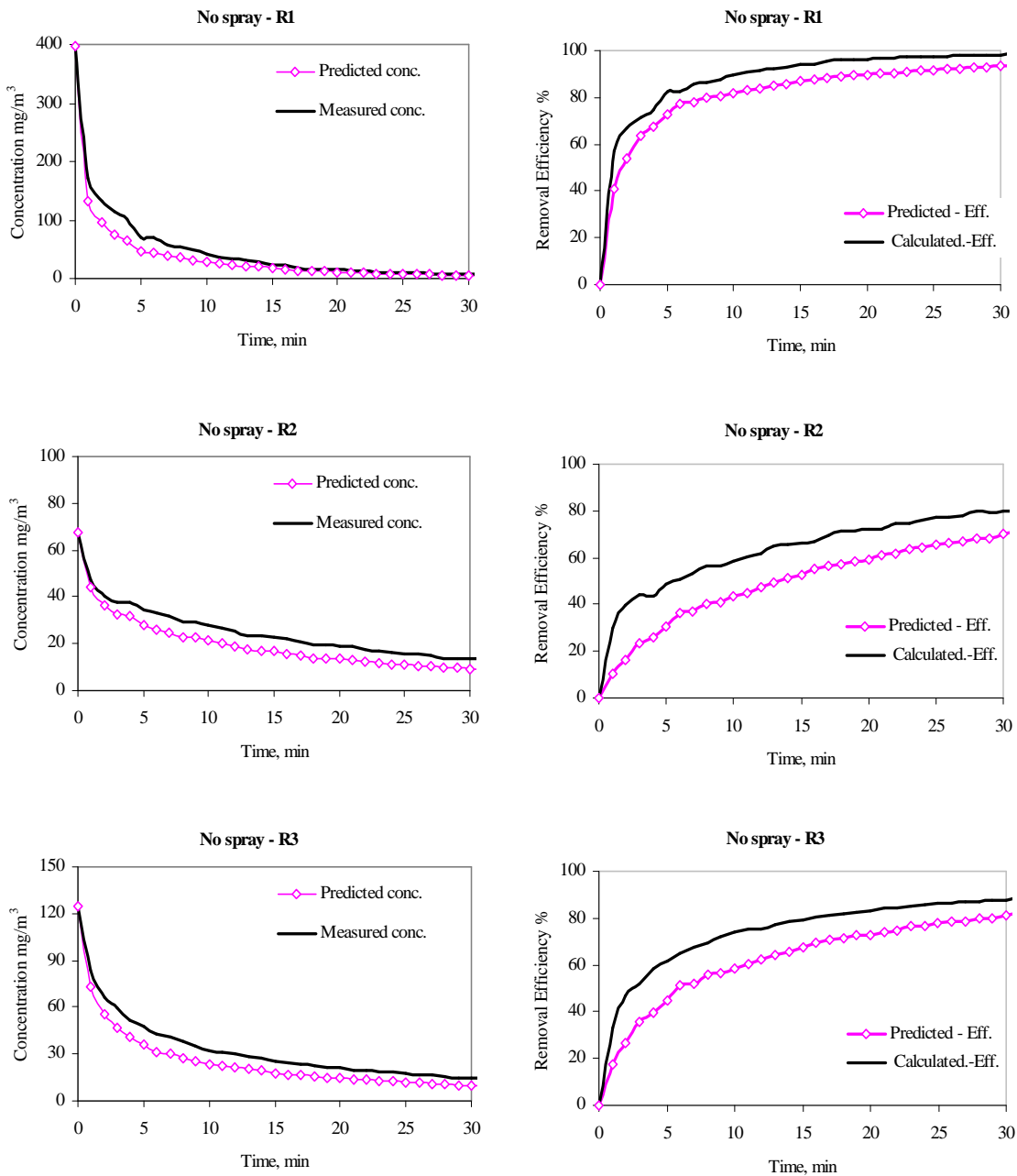


Figure 6-31 Measured and predicted values of mass concentration and removal efficiency for NaHCO₃ for the no spray case. Data were obtained by the Tapered Element Oscillating Microbalance (TEOM).

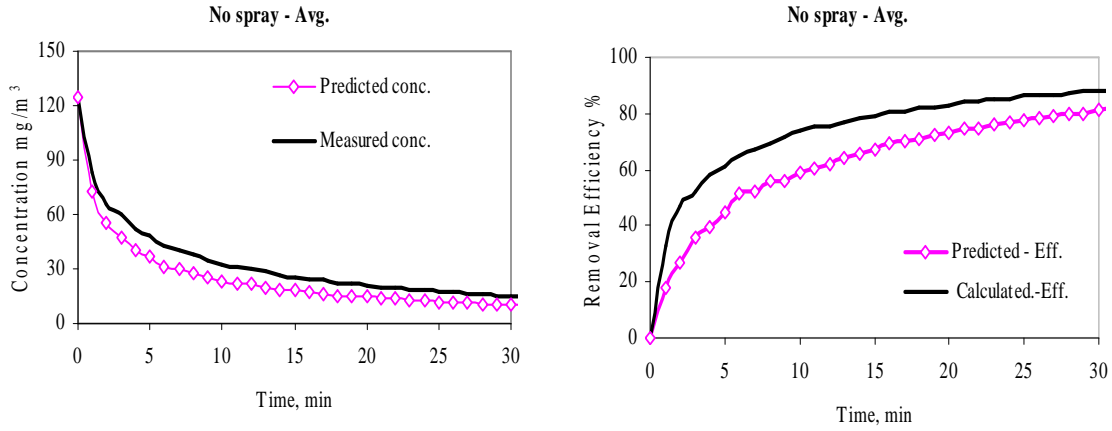


Figure 6-32 Average of measured and predicted values of mass concentration and removal efficiency for NaHCO₃ for the no spray case. Data were obtained by the Tapered Element Oscillating Microbalance (TEOM).

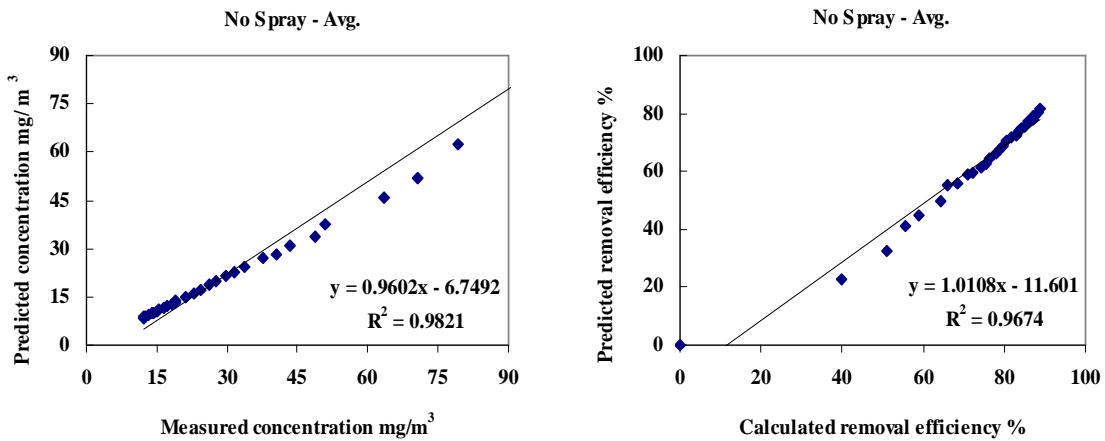


Figure 6-33 Correlation between measured and predicted values of mass concentration and removal efficiency at $t=10$ min for NaHCO₃ using no water spray.

6.4.3 Statistical indices

To further compare predicted and measured values, the ASTM standard D5157 (ASTM, 2002) was used. This standard assesses the performance of indoor air quality models by comparing indoor concentrations predicted by a model, C_p and observed concentrations, C_o . The following indices were used:

- (1) Correlation coefficient, with a value of 1 indicating a strong, direct relationship between C_p and C_o , a value of 0 indicating no relationship, and a value of -1 indicating a strong but inverse relationship.
- (2) Line of regression, which describes the best-fit relationship between C_p and C_o ideally exhibiting a slope, \mathbf{b} , of one and an intercept, \mathbf{a} , of zero.
- (3) Normalized mean square error (NMSE), which is a measure of the magnitude of prediction error relative to C_p and C_o . NMSE is calculated using Eqn 6.31. NMSE will have a value of 0 when there is perfect agreement for all pairs of C_p and C_o and will tend toward higher values as C_p and C_o differ by greater magnitudes:

$$NMSE = \frac{\left[\frac{\sum_{i=1}^n (C_{pi} - C_{oi})^2}{n} \right]}{\left[\left(\sum_{i=1}^n \frac{C_o}{n} \right) \left(\sum_{i=1}^n \frac{C_p}{n} \right) \right]} \quad (6.31)$$

- (4) Normalized fractional bias (FB), which can be calculated by the following equation:

$$FB = \frac{2 \times (C_{pm}) - (C_{om})}{(C_{pm}) + (C_{om})} \quad (6.32)$$

The FB will have a value of 0 when C_p and C_o agree perfectly and will tend towards -2 or +2 as these quantities differ by greater magnitudes.

(5) Fractional bias based on variance (FS), which can be calculated by the following equation:

$$FS = \frac{2 \times (\delta_p^2 C_{pm} - \delta_o^2 \times C_{om})}{(\delta_p^2 C_{pm} + \delta_o^2 C_{om})} \quad (6.33)$$

As indicated in the ASTM standard (ASTM, 2002), considering the potential consequences of measurement uncertainties, the following values can be taken as generally indicative of adequate model performance:

- (1) Correlation coefficient of 0.9 or greater,
- (2) Regression slope between 0.75 and 1.25,
- (3) Regression intercept 25 % or less of the average measured concentration,
- (4) NMSE of 0.25 or lower,
- (5) FB of 0.25 or lower, and
- (6) FS of 0.5 or lower

The indices for evaluating the adequacy of the predictive model are listed in Tables 6-3 and 6-4, and the means of these indices are summarized in Table 6-5. The mean values of all indices were within the acceptable ranges. Overall, the criteria for the adequacy of the statistical indices were generally satisfied, indicating that predicted and measured values were in good agreement.

Table 6-3 Values of model performance indices for number and mass concentrations.

	Powder type	Treatment	Rep	Statistical indices						
				r	b	a	0.25 of Mean C_m	NMSE	FB	FS
Mass Concentration	Corn starch	Charged spray	R1	0.99	1.05	-0.94	2.69	0.10	-0.04	0.41
			R2	0.98	0.92	-2.63	3.77	0.31	-0.29	-0.76
			R3	1.00	0.96	-0.82	2.33	0.09	-0.13	-0.40
		No spray	R1	0.99	0.97	-17.38	12.59	0.31	-0.47	-0.61
			R2	0.99	1.00	-15.74	13.45	0.16	-0.34	-0.29
			R3	0.99	0.90	-5.65	7.08	0.22	-0.35	-0.95
	NaHCO ₃	Charged spray	R1	0.94	0.96	-4.34	4.45	0.26	-0.33	-0.39
			R2	0.98	0.84	-2.51	3.53	0.33	-0.41	-1.31
			R3	0.97	0.96	-4.16	5.02	0.24	-0.28	-0.49
		No spray	R1	1.00	0.94	-8.55	12.90	0.13	-0.25	-0.61
			R2	0.99	1.04	-6.41	6.41	0.06	-0.24	0.11
			R3	1.00	0.99	-7.27	8.47	0.07	-0.26	-0.31
Number Concentration	Corn starch	Charged spray	R1	0.98	1.04	-3.46	6.93	0.12	-0.09	0.38
			R2	0.99	1.26	-5.01	7.84	0.20	0.09	1.54
			R3	0.98	1.04	-2.72	6.57	0.12	-0.06	0.46
		No spray	R1	1.00	0.98	2.79	8.33	0.01	0.06	-0.11
			R2	0.97	0.98	1.08	4.87	0.06	0.03	0.10
			R3	0.99	1.21	-0.23	2.58	0.07	0.17	1.42
	NaHCO ₃	Charged spray	R1	0.99	0.69	-3.98	23.79	0.46	-0.42	-1.86
			R2	1.00	1.25	-0.42	10.31	0.15	0.22	1.58
			R3	1.00	0.87	-1.24	15.79	0.06	-0.16	-1.09
		No spray	R1	1.00	1.08	-0.10	27.95	0.02	0.08	0.70
			R2	1.00	0.98	2.30	26.49	0.01	0.00	-0.19
			R3	1.00	1.08	-3.38	37.66	0.02	0.06	0.68

Table 6-4 Values of the model performance indices for removal efficiency.

	Powder type	Treatment	Rep	Statistical indices						
				r	b	a	0.25 of Mean C_m	NMSE	FB	FS
Mass Concentration	Corn starch	Charged spray	R1	0.99	1.08	-8.89	22.78	0.00	-0.02	0.66
			R2	0.99	1.05	-4.75	22.80	0.00	0.00	0.45
			R3	0.97	1.11	-12.75	23.24	0.00	-0.03	0.92
		No spray	R1	0.99	1.06	-4.03	21.82	0.00	0.02	0.56
			R2	0.98	1.05	-4.41	22.93	0.00	0.00	0.50
			R3	1.00	1.04	-4.91	20.98	0.00	-0.01	0.36
	NaHCO ₃	Charged spray	R1	0.99	1.01	0.48	21.06	0.00	0.02	0.24
			R2	0.99	0.92	8.50	19.95	0.00	0.03	-0.53
			R3	0.97	1.04	-5.41	22.95	0.00	-0.01	0.55
		No spray	R1	0.99	0.99	-6.50	21.76	0.01	-0.08	-0.05
			R2	0.98	1.02	-15.29	15.48	0.07	-0.25	0.14
			R3	0.98	1.03	-13.66	18.20	0.03	-0.17	0.21
Number Concentration	Corn starch	Charged spray	R1	0.84	0.64	30.58	12.07	0.26	0.24	-1.50
			R2	0.90	1.11	-1.45	15.40	0.06	0.08	1.39
			R3	0.89	0.73	23.05	13.44	0.13	0.15	-1.22
		No spray	R1	0.84	0.61	13.04	15.41	0.09	-0.20	-1.76
			R2	0.92	0.57	14.65	10.96	0.19	-0.10	-1.92
			R3	0.89	0.99	-8.71	10.33	0.18	-0.25	0.59
	NaHCO ₃	Charged spray	R1	0.70	0.50	51.06	15.89	0.09	0.27	-1.67
			R2	0.98	1.06	-10.68	20.06	0.01	-0.08	0.55
			R3	0.98	0.87	15.46	18.14	0.01	0.08	-0.84
		No spray	R1	0.79	0.58	9.94	14.82	0.19	-0.29	-1.78
			R2	0.79	0.58	10.83	10.86	0.16	-0.18	-1.73
			R3	0.94	0.91	2.70	15.45	0.02	-0.05	-0.30

Table 6-5 Mean values of model performance indices for concentration and removal efficiency.

	Parameter	Mean value	Indicative of adequate model
Concentration	a	-3.78	<10.91
	b	1.00	0.75-1.25
	r	0.99	>0.9
	NMSE	0.15	<0.25
	FB	-0.14	<0.25
	FS	-0.08	<0.5
Removal Efficiency	a	3.28	<17.78
	b	0.90	0.75-1.25
	r	0.93	>0.9
	NMSE	0.06	<0.25
	FB	-0.04	<0.25
	FS	-0.26	<0.5

6.5 Conclusions

The following conclusions were drawn from this research:

- A review of literature indicated that the scrubbing process of a single droplet as a collector has been discussed theoretically in many articles in literature. Only a few articles, however, reported the overall effects of a spray on the reduction of airborne particles. Furthermore, very few published research related the experimental data to theoretical analysis.
- The model based on coagulation was able to predict the particle concentration and the removal efficiency (number and mass based) with a good accuracy. Predicted values agreed well with measured values.

6.6 References

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CHAPTER 7 - ELECTROSTATICALLY-ASSISTED WET SCRUBBER FOR CONTROLLING DUST IN LIVESTOCK BUILDINGS

7.1 Abstract

A prototype electrostatically-assisted particulate wet scrubber (EAPWS) was developed and tested under laboratory and field conditions. Under laboratory conditions, the EAPWS with the negatively-charged water spray had significantly higher particle removal efficiency ($\eta=79\%$) than either the uncharged wet scrubber ($\eta=58\%$) or the control (i.e., only the fan was operated; $\eta=21\%$). There was no significant difference in removal efficiency between the negatively-charged EAPWS (79%) and the positively-charged EAPWS (73%). For the negatively-charged EAPWS, an optimum ratio between the air velocity and amount of water spray for each specific mixing volume existed in which the removal efficiency decreased as the air velocity increased. Field tests in a swine building proved that the EAPWS was effective in removing airborne dust.

7.2 Introduction

Previous studies have shown that dust along with viable microorganisms, fungi, and adsorbed gases in livestock buildings have been implicated as contributors to the increased incidence of respiratory disorders among workers (Dosman et al., 1988; Donham et al., 1989; Zejda et al., 1993; Zejda et al., 1994; Senthilselvan et al., 1997a). In addition, reducing dust concentration within buildings has resulted in improvement in human respiratory responses (Senthilselvan et al., 1997b; Zhang et al., 1998).

A wet scrubber is commonly used for the collection of particles and odors from air streams because of its high collection efficiency and relatively low cost. The major collection

mechanisms in a wet scrubber include inertial collection, interception, and diffusion. In some cases, electrostatics has been used to augment particle collection efficiency of water droplets (Lear et al., 1976; Hassler and Birgitta, 1978). In these scrubbers, electrical forces are introduced by imposing electrostatic charges onto the fine droplets before they enter the inlet of wet scrubbers. The force of mutual electrical attraction (Coulombic force) drives the particles toward the droplets. This induced electrical charge on droplets and particles contributes to the improvement of the overall collection efficiency of an electrostatic scrubber over conventional scrubbers. In addition to particle removal, wet scrubbing is a well known method for removing water-soluble gases, including ammonia and odorous compounds. Licht and Miner (1979) found that there was a highly significant relationship between odor removal and particle removal by scrubbers.

The study in Chapter 5 has indicated the potential of charged-water spray in reducing dust concentration in enclosed spaces. This study was then conducted to develop a prototype of an air cleaning device that uses charged water spray and that can be used in livestock buildings. Specific objectives were to:

1. Develop a prototype electrostatically-assisted particulate wet scrubber (EAPWS) for dust control in livestock buildings; and
2. Evaluate the EAPWS under laboratory and field conditions.

7.3 Materials and Methods

7.3.1 Development of the electrostatically-assisted particulate wet scrubber (EAPWS)

The EAPWS was built based on the counter-current wet scrubber design. It uses an air-assisted induction charging nozzle instead of the ordinary spray nozzle. The EAPWS consists of

the following components: (1) axial fan, (2) mixing chamber, (3) electrostatically-charged water spraying system, and (4) exhaust duct (Fig. 7-1).

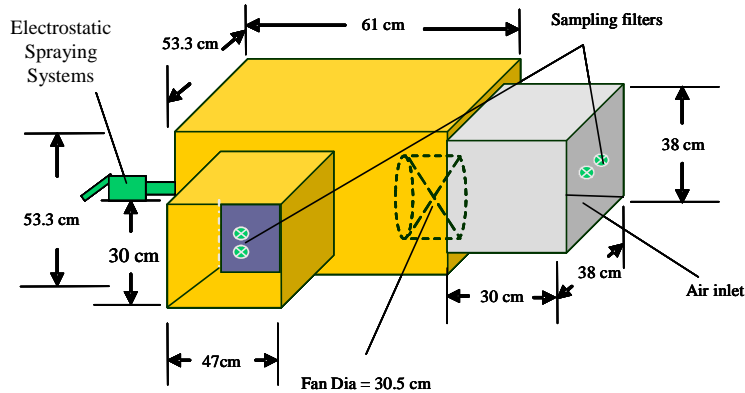


Figure 7-1 Schematic diagram showing the electrostatically-assisted particulate wet scrubber (EAPWS).

The axial fan has a diameter of 31cm and can provide variable volumetric flow rates up to 27 m³/min. The fan was mounted in a fiberglass duct and motor speed was controlled by a voltage controller. Figure 7-2 shows the relationship between the fan speed setting and scrubber air velocity. The air velocity within the scrubber was measured at various points at the scrubber inlet and outlet cross-section by conducting a velocity traverse for the sampling area. An anemometer (Model 8347, TSI Incorporated, Shoreview, MN) was used to measure the air velocity.

The mixing chamber has dimensions of 53 cm × 53 cm × 61 cm (0.17 m³). The upper and lower sides are covered with sheet metal for grounding purposes. The exhaust duct has a cross section of 47 cm × 30 cm.

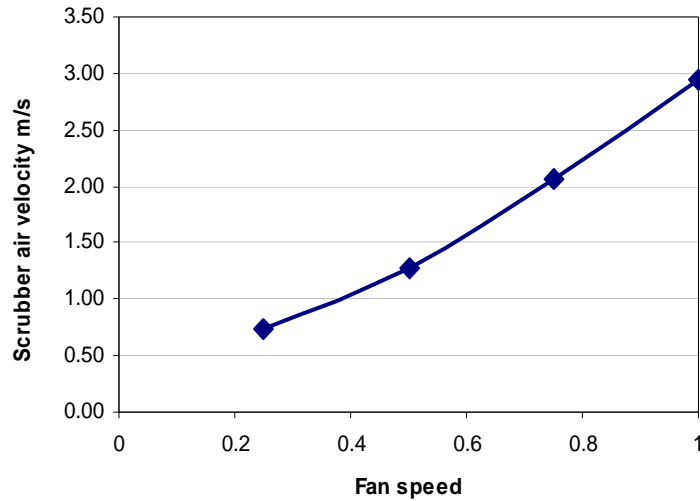


Figure 7-2 Relationship between EAPWS air velocity and fan speed.

The charged water spray is produced by a water spraying device (Electrostatic Spraying Systems, Inc., Watkinsville, GA), which uses induction charging. In this study, the spraying system was operated at a liquid flow rate of 120 mL/min (water tank pressure of 15 psig). Charging levels were approximately -6.5 mC/kg for the negatively-charged EAPWS and approximately +7.2 mC/kg for the positively-charged EAPWS. The spraying nozzle was positioned on the side of the mixing chamber facing the fan outlet. The spraying direction was facing the air stream. Table 7-1 summarizes the charge measurement for the air that is coming out from the scrubber outlet.

Table 7-1 Charge measurement for the air that is coming out from the scrubber outlet.

Scrubber fan	Nozzle	Charge (nC) ¹
OFF	OFF	0.13
ON	OFF	0.16
	Air only without charging	0.38
	Air only with charging (negative)	-0.41
	Water spray without charging	0.15
	Water spray with charging (negative)	-114

¹The charge was measured using a dynamic Faraday cage sampler one minute after spraying.

7.3.2 Laboratory evaluation

The EAPWS was tested in the laboratory to determine the effects of scrubber air velocity (i.e., 0.73, 1.27, 2.07, and 2.93 m/s), grounding the chamber walls, charge polarity (negative vs. positive), and type of particle (corn starch and NaHCO₃) on its performance. It was also compared to the case in which the scrubber was operated with uncharged water (i.e., uncharged scrubber) and that in which only the fan (i.e., no water spray) was operated. The case in which only the fan was operated served as the control. All experiments were conducted in an enclosed experimental chamber with dimensions of 3.6 m x 2.4 m x 2.4 m (Fig. 7-3). The air temperature and relative humidity inside the chamber were maintained at 25°C and 40%, respectively. For each experiment, the experimental chamber was prepared by cleaning the surfaces and running its air filtration system. The ventilation and air filtration systems of the chamber were not operated during the experiment, so that air exchange in the room was primarily through natural infiltration/exfiltration.

Particles were dispersed into the experimental chamber by using a pressurized canister at 80 psig. A nominal mass of 20 g was used; the actual mass deployed ranged from 7.4 to 12.5 g for corn starch and from 2.7 to 8.3 g for NaHCO₃. Dispersion took approximately 2 sec. To

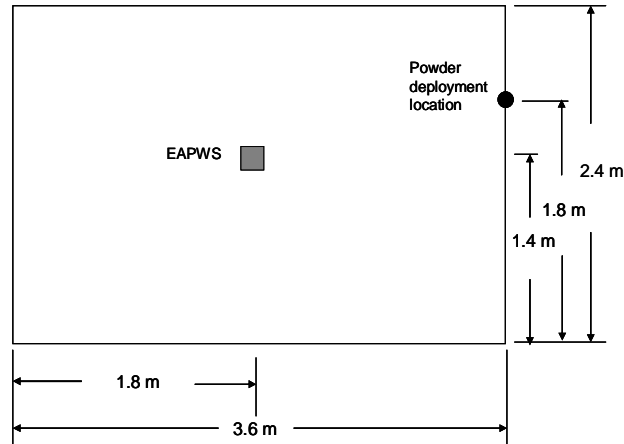
further disperse the particles inside the chamber, two mixing fans inside the chamber were operated for about 2 min after deployment of the particles. The scrubber fan and the water spray (charged spray for the EAPWS and uncharged for the uncharged wet scrubber) were operated starting at t=2 min (i.e., 2 min after particle deployment). One minute after (i.e., t= 3 min), the sampling pump for the filter samplers (described later in this section) was operated for 2 min. Again, for the control, only the fan was turned on; the water spray was not use.

For all cases, air sampling was done under isokinetic conditions at specific locations within the inlet and outlet ducts. The filter samplers had 11-mm probe inlet diameter and a 37-mm filter assembly (Fig. 7-4). The sampling heads were positioned within the sampling area facing the air stream. The filter holder was attached to a rigid tube, which was connected by flexible tubing to a vacuum pump. The air sampling flow rate was adjusted to isokinetic conditions by varying the sampling flow rate to match the air velocity at the inlet area of the sampler with the air stream velocity outside the sampler. The required sampling flow rates for isokinetic sampling (Table 7-2) were determined by conducting a velocity traverse over the sampling area prior to sampling (Predicala and Maghirang, 2004). The dust collection filters (Type AE, SKC, Eighty Four, PA) were conditioned by placing them in the oven for 24 h at 103oC before and after sampling. Filter conditioning was done to minimize the effect of humidity and collected water droplets on filter weights. All filters were weighed in an electronic microbalance (Model AG245, Mettler-Toledo, Hightstown, NJ) with a sensitivity of 0.01 mg.

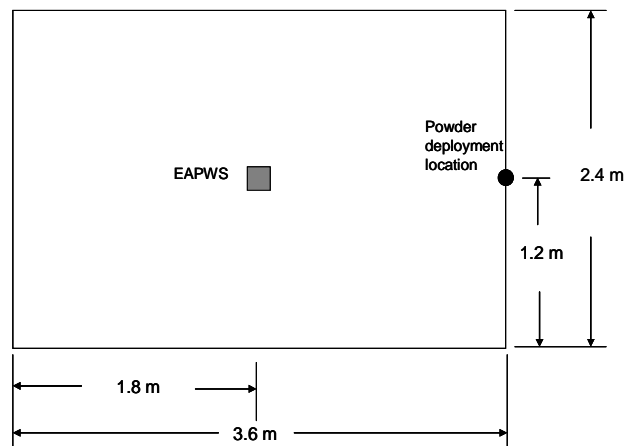
The effectiveness of the EAPWS was determined by comparing the dust concentrations at the inlet and exhaust of the scrubber. The removal efficiency of the EAPWS was calculated using the following equation:

$$\eta = \frac{C_i - C_o}{C_i} \quad (7.1)$$

where η is the removal efficiency of scrubber, C_i is the particle mass concentration at the scrubber inlet, and C_o is the particle mass concentration at the scrubber exhaust. The mean η values were analyzed statistically by using PROC GLM of SAS (Version 9.1, SAS Institute, Inc., Cary, NC). Treatment means were compared at a level of significance of 5%.



(a)



(b)

Figure 7-3 Schematic diagram of the experimental chamber and setup: (a) elevation and (b) plan view).

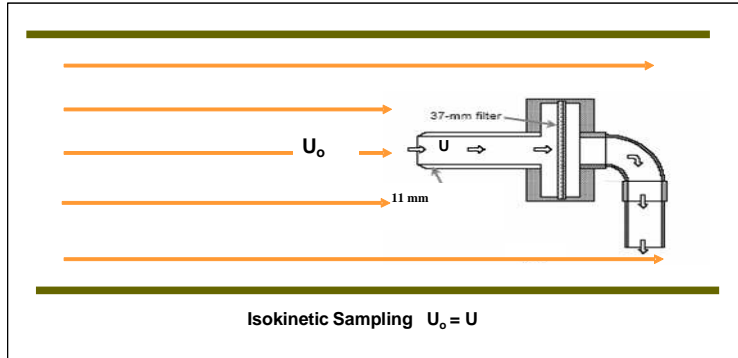


Figure 7-4 Schematic diagram of a dust sampler with 11-mm probe inlet diameter and a 37-mm filter assembly. U_0 is the mean free stream velocity and U is the average air velocity through the sampling probe.

Table 7-2 Relationship among the fan speed setting, mean duct airflow rate, and sampling flow rate.

Fan speed setting	Duct average airflow rate (m^3/min)	Sampling flow rate ¹ (L/min)
0.25	6.4	4
0.50	11	6.8
0.75	17.9	10.8
1.00	25.4	14.8

¹Sampling flow rate was based on the mean air velocity at the sampling point.

7.3.3 Field evaluation

Field evaluation involved testing the EAPWS in a swine building. The EAPWS was installed near the center of the building (Fig. 7-5). The evaluation compared the following cases: (1) EAPWS with negatively-charged water spray or negatively-charged EAPWS; (2) wet scrubber with uncharged-water spray or uncharged scrubber; and (3) fan with no water spray

(i.e., control). For all cases, the air velocity was fixed at 1.27 m/s. Table 3 summarizes the test conditions during the sampling period. Similar to the laboratory evaluation, the effectiveness of the device was evaluated by measuring the dust mass concentrations upstream and downstream of the device.



Figure 7-5 Photographs showing the scrubber inside the swine building during testing.

Table 7-3 Measured parameters inside the swine building during the testing period.

Parameter	Mean Value
Dust mass concentration (mg/m^3)	0.77
Temperature (C)	24.5
Relative humidity (%)	55.6
True density of dust particles (g/cm^3)	1.84
True density of animal feed particles (g/cm^3)	1.53
Net charge-to-mass ratio of airborne particles (mC/kg)	+0.68
Geometric mean diameter of particles (μm)	9.34
Geometric standard deviation of particles	2.11

7.4 Results and Discussion

7.4.1 Laboratory evaluation

Figure 7-6 summarizes the effect of air velocity on the efficiency of the negatively-charged EAPWS for corn starch. The mean η values were 32% at full speed (2.93 m/s), 43% at the air velocity of 2.07 m/s, 78.6% at air velocity of 1.27 m/s, and 79% at air velocity of 0.73 m/s. The decrease in η with increasing air velocity could be due to the decrease in collisions between the charged water droplets and the particles as air velocity increases. These results suggest that there is an optimum ratio between the air velocity and amount of water spray for each specific mixing volume that controls the residence time, and increases collection surfaces which results in higher collection of particles by the water droplets. An air velocity of 1.27 m/s was then used throughout the study.

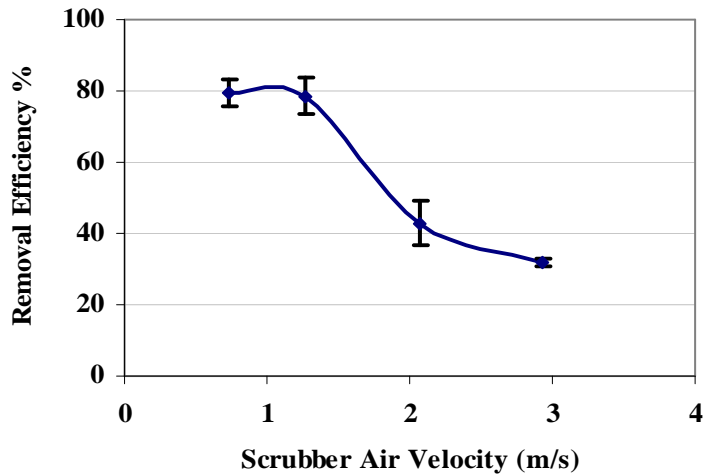


Figure 7-6 Effect of EAPWS air velocity on the removal efficiency of the EAPWS (negatively charged) for corn starch. Error bars represent one standard deviation.

Grounding the inner surface of the mixing chamber did not significantly improve the effectiveness of the EAPWS for corn starch. For the negatively-charged EAPWS, the mean η values were 67.9% (SD=7.4%) with grounding and 78.6% (SD=5.22%) for the ungrounded case. For the positively-charged EAPWS, on the other hand, the mean η values for were 67.8% (SD=11.8%) with grounding and 73% (SD=4.60%) for the ungrounded case.

Table 7-4 summarizes the η values for corn starch for the negatively-charged EAPWS, uncharged scrubber, and control (i.e., only the fan was operated). The negatively-charged EAPWS had significantly ($P<0.05$) higher η (78.6%) than either the control ($\eta=20.9\%$) or the uncharged wet scrubber ($\eta=57.7\%$). The larger mean η value for the EAPWS can be accounted for by the enhanced removal of particles due to electrostatic forces that enhance the coagulation between the water droplets and dust particles. The uncharged wet scrubber had significantly ($P<0.05$) higher η than the control; this may be accounted for by the removal of particles by the water spray.

Table 7-4 also shows that the spray charge polarity (negative vs. positive) did not significantly affect the η value of the EAPWS for corn starch. Results for NaHCO_3 were similar to those for corn starch; the η value was not significantly affected by the type of polarity.

Comparison of the two types of particles shows that the mean η value was higher for corn starch than for NaHCO_3 (Table 7-4). This could be due to the difference in size between the two types of particles. NaHCO_3 had a smaller geometric mean diameter than corn starch. Smaller particles are generally more difficult to remove than the larger particles, even with electrostatic deposition.

Table 7-4 Removal efficiencies (mass basis) for the EAPWS, uncharged scrubber, and fan (i.e., no water spray).

Treatment	Corn starch		NaHCO ₃	
	η^1	SD	η^1	SD
Negatively-charged EPWS	78.6 a	5.22	55.1 a	13.1
Positively-charged EPWS	73.0 a	4.60	68.0 a	4.6
Uncharged scrubber	57.7 b	3.67	-	-
Control (i.e., only the fan was operated)	20.9 c	3.04	-	-

¹Column means followed by the same letter are not significantly different at 95% level of confidence.

7.4.2 Field evaluation

Table 7-5 summarizes the mean η values for the swine building. The negatively-charged EAPWS was significantly more effective in removing dust particles ($\eta = 70.3\%$) than either the uncharged scrubber ($\eta = 46.2\%$) or the control (i.e., only fan was operated) ($\eta = 17.1\%$). Comparison of the laboratory and field evaluations indicated that the mean η value for the EAPWS was slightly lower in the swine building than in the experimental chamber. The lower η value could be due to differences in concentration, size distribution, and characteristics of the particles between the swine building and the experimental chamber. For example, the concentration was much lower in the swine building than in the chamber ($<1 \text{ mg/m}^3$ for the swine building and $>5 \text{ mg/m}^3$ for the experimental chamber). With lower concentration, collisions between the water droplets and the particles are expected to be lower.

Table 7-5 Removal efficiencies (mass basis) of charged water spray, uncharged water spray, and no water spray.

Treatment	η^1	SD
EAPWS (negatively-charged)	70.3 a	8.7
Uncharged scrubber	44.6 b	5.9
Control (i.e., only the fan was operated)	17.1 c	9.7

¹Column means followed by the same letter are not significantly different at 5% level of significance.

7.5 Conclusions

A prototype electrostatically-assisted particulate wet scrubber (EAPWS) was developed and tested under both laboratory and field conditions. The following conclusions were drawn from this research:

- Laboratory and field evaluations indicated that the EAPWS had significantly higher particle removal efficiency than either the control (i.e., no water spray) or the uncharged wet scrubber.
- The negatively-charged EAPWS did not significantly differ from the positively-charged EAPWS in terms of removal efficiency.
- The removal efficiency decreased as the EAPWS air velocity increased.

7.6 References

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CHAPTER 8 - CONCLUSION AND RECOMMENDATIONS

8.1 Summary and Conclusions

The potential of electrostatically-charged water spray in controlling dust concentration in livestock buildings was examined in this research through a combination of laboratory research, field research, and modeling. The following conclusions were drawn from this research:

- A dynamic Faraday-cage sampler for measuring the charge of particles was successfully developed. The sampler was able to measure the net charge-to-mass ratio of solid and liquid particles with %error ranging from <1% to 8%.
- Laboratory evaluation showed that the charged-water spray was significantly more effective in reducing dust concentration than the uncharged-water spray. The efficiency was affected by spray duration; longer charged-water-spray durations (4 and 6 min) resulted in significantly higher particle removal efficiency than the shorter (2 min) duration
- A coagulation-based model was able to adequately predict the reduction in particle concentration and removal efficiency of charged water spray.
- Laboratory and field evaluations of a prototype electrostatically-assisted particulate wet scrubber (EAPWS) indicated that the EAPWS had significantly higher particle removal efficiency than either the control (i.e., no water spray) or the uncharged wet scrubber.

8.2 Recommendations for Further Studies

The electrostatically-charged water spray proved to be an effective method in reducing airborne dust concentration; however, more work is needed to adapt and use this technology in the field. The following are recommended for future studies:

1. For charge measurement in livestock buildings, more measurements are needed for other types of buildings and environmental conditions. There is a need to determine the charge of airborne dust particles in different environments.
2. Further research is needed to study different parameters that affect the efficiency of the electrostatically-assisted particulate wet scrubber in the field environment, in addition to the scrubber design parameters.
3. For the modeling of the removal efficiency and dust reduction by charged water spray, more studies are needed to study different parameters that control the value of coagulation coefficients, specifically the mechanical and electrostatic effects.

Appendix A

Characterization of Charged Water Spray

Appendix A - Characterization of the Charged Water Spray

A.1 Description of the Spraying System

The charged spray was generated by induction charging and air-assisted nozzle by a commercially available electrostatic spraying system (Electrostatic Spraying Systems, Inc., Watkinsville, GA). Figure A-1 shows a schematic diagram of the spraying system. The spraying system works with the following conditions:

1. Fluid resistivity range: 20 ohm-cm to 50,000 ohm-cm * 0.6 kV to 1.2 kV normal operating voltage range
2. Operating current: 0.10 - 0.80 mA
3. Air pressure range: 25 to 80 psig
4. Air consumption: 2.9 to 10 cfm
5. Liquid flowrate: 50 to 200 mL/min (120 ml/min at 15 psig tank pressure)
6. Charging level: -6.5 mC/L

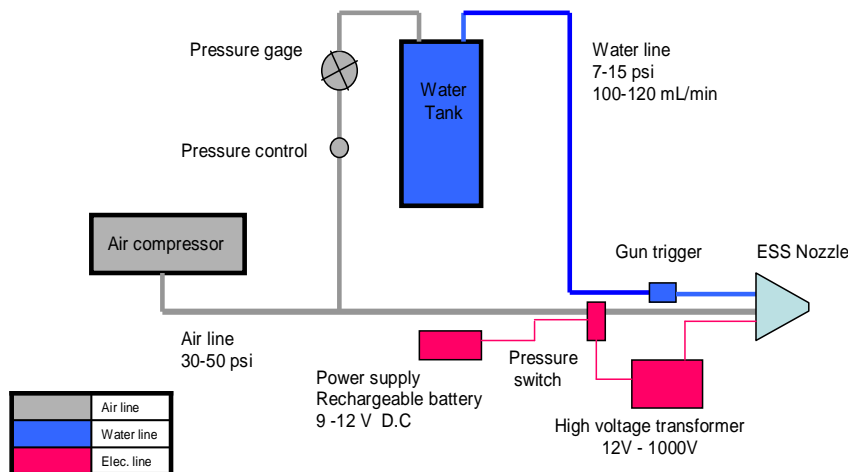


Figure A-1 Schematic diagram of the spraying system.

A.2 Water Use and Spray Cone Diameter

Experiments were conducted to determine the water usage, and spray cone characteristics. Figure A-2 shows the water usage as a function of time and pressure. Water use ranged from 1.6 mL/sec for a pressure of 10 psig to 2.3 mL/sec for a pressure of 20 psig. Figure A-3 summarizes the diameter of the spray cone as a function of distance from the spraying nozzle. Spray cone diameter ranged from 10 to 35 cm depending on the distance from the tip of the nozzle.

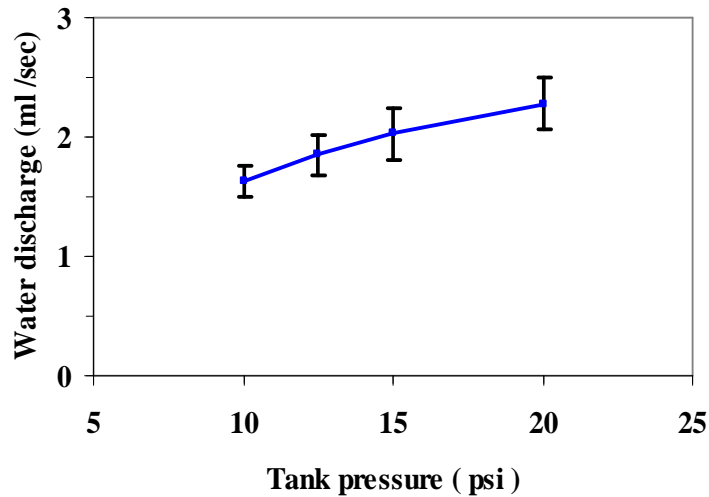


Figure A-2 Water consumption by the electrostatic spraying system as a function of tank pressure. Error bars represent one standard deviation.

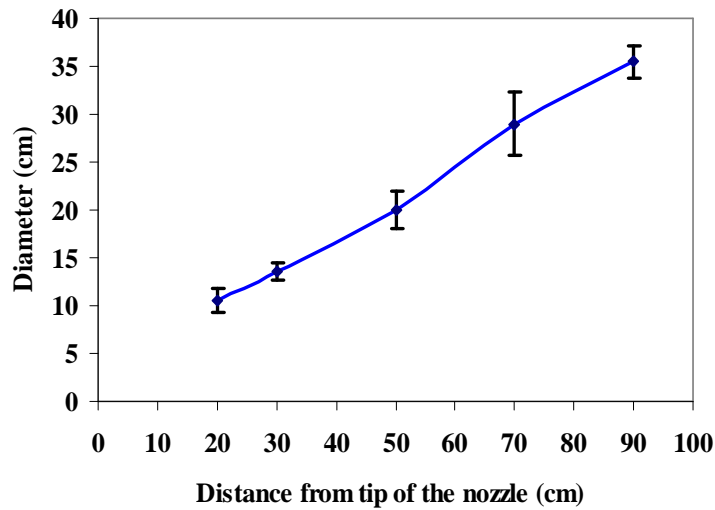
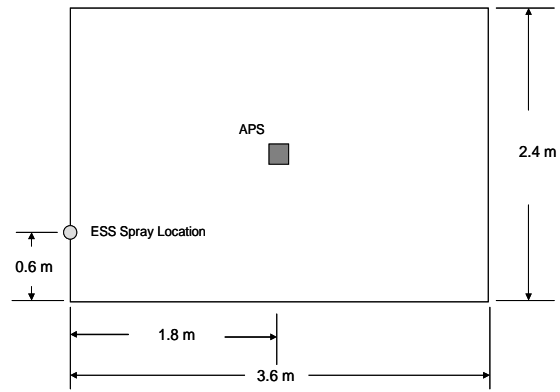


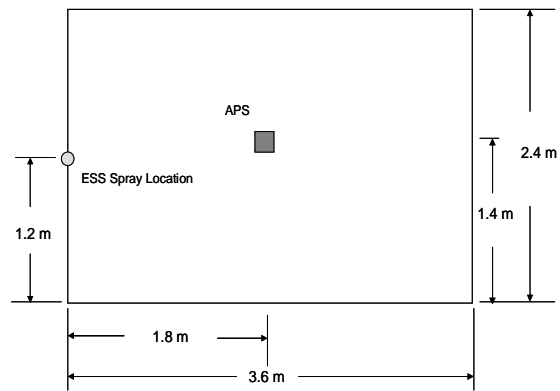
Figure A-3 Size of the spray cone produced by the electrostatic spraying nozzle.

A.3 Droplet Size Distribution

The size distribution and number concentration of the airborne droplets were monitored by using the APS spectrometer. This spectrometer measures the equivalent aerodynamic diameter of particles from 0.54 to 20 μm , and uses an air sampling rate of 1.0 L/min. The spectrometer was connected to a dilution unit, which was set at a 100:1 dilution ratio. Both the dilution unit and the APS were located near the center of the experimental chamber (Fig. A-4). The spraying system was operated at a liquid flow rate of 120 mL/min (water tank pressure of 15 psig). Figures A-5 and A-6 show the droplet size distributions, based on number and mass concentrations, respectively.



(a)



(b)

Figure A-4 Schematic diagram of the experimental chamber and setup: (a) elevation and (b) plan view.

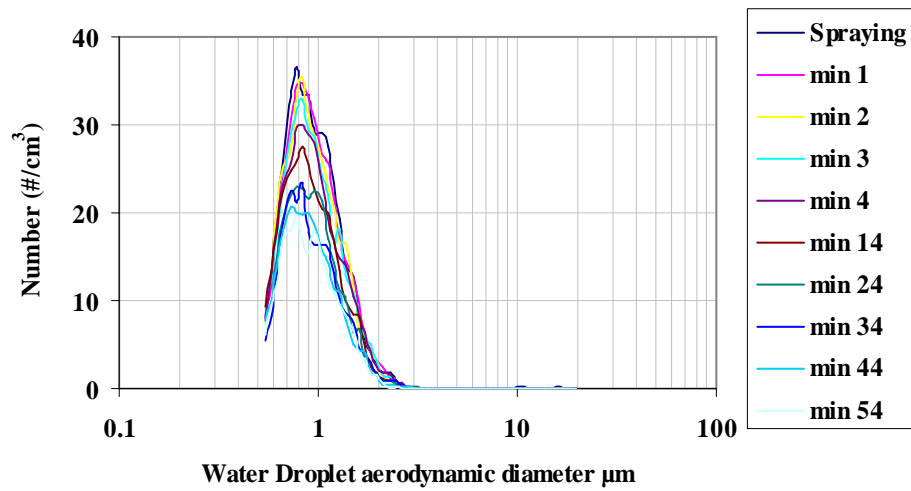


Figure A-5 Droplet size distribution (number concentration) for the electrostatic spraying system during and after spraying.

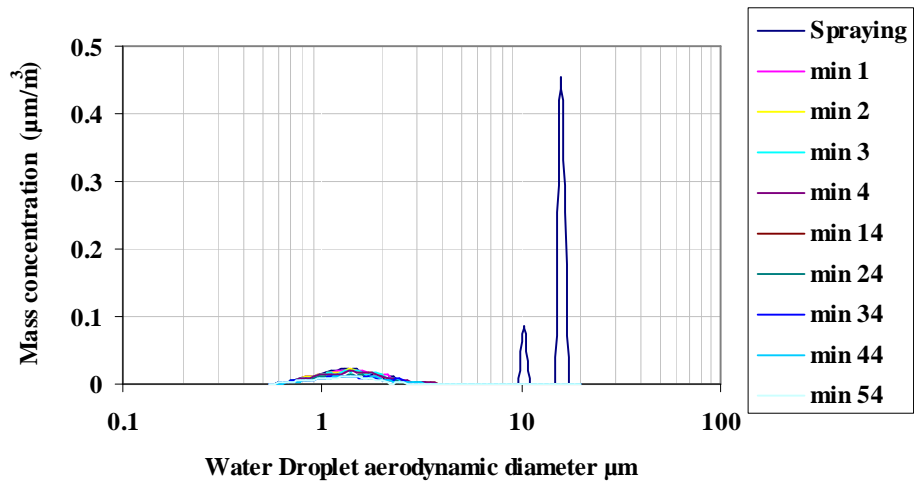


Figure A-6 Droplet size distribution (mass concentration) for the electrostatic spraying system during and after spraying.

Appendix B
Experimental Data

Appendix B - Experimental Data

Data for Chapter 3

Table B-1 Calibration of the dynamic Faraday-cup sampler.

Voltage V	Capacitor μF	Calculated charge nC	Direct connection nC	Faraday sampler nC
1	0.001	1	1.09	1.05
	0.01	2	2.10	2.10
	0.1	3	3.10	3.25
2	0.001	10	10.47	10.20
	0.01	20	20.80	20.70
	0.1	30	31.30	31.20
3	0.001	100	101.86	100.20
	0.01	200	202.90	203.80
	0.1	300	305.20	305.10

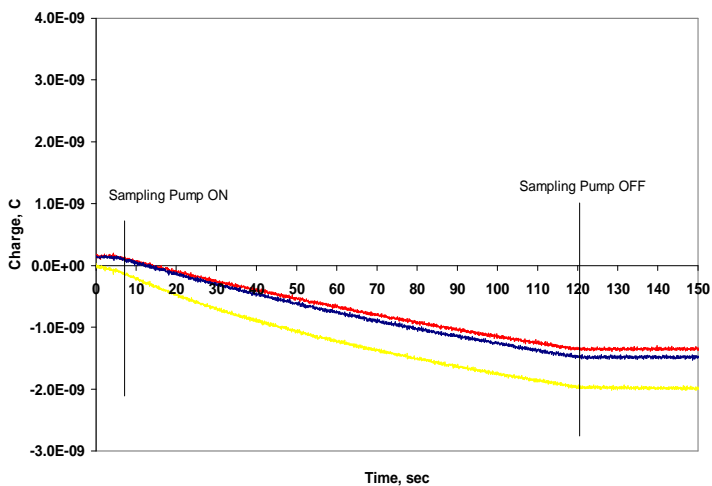


Figure B-1 Charge of negatively charged water spray as measured by the dynamic Faraday-cup sampler.

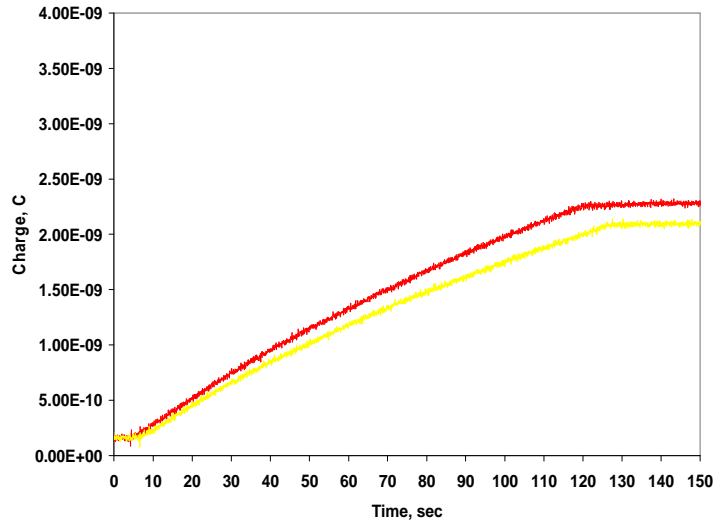


Figure B-2 Charge of the positively charged water spray as measured by the dynamic Faraday-cup sampler.

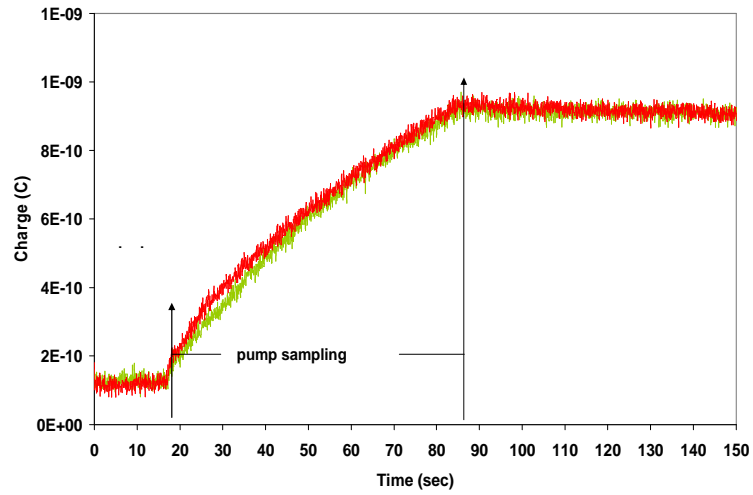


Figure B-3 Charge of NaHCO_3 as measured by the dynamic Faraday-cup sampler.

Data for Chapter 4

Table B-2 Mean values of the particle size distribution statistics. Size distribution was measured with an Aerodynamic Particle Sizer™ (APS) spectrometer.

Sample range	Median (μm)		Mean (μm)		GMD(μm)		Mode (μm)		GSD	
	Number	Mass	Number	Mass	Number	Mass	Number	Mass	Number	Mass
1-10	0.70	11.30	1.16	10.80	0.87	9.44	0.67	17.10	1.82	1.81
11-20	0.70	12.20	1.21	11.50	0.89	10.20	0.67	17.20	1.87	1.78
21-30	0.69	11.00	1.16	10.90	0.87	9.47	0.63	17.20	1.84	1.82
31-40	0.70	11.60	1.30	11.10	0.93	9.82	0.63	16.00	1.96	1.75
41-60	0.68	11.50	1.18	10.70	0.87	9.46	0.63	14.90	1.87	1.78
61-70	0.69	11.60	1.21	10.90	0.89	9.57	0.63	13.80	1.89	1.79
71-80	0.68	10.80	1.20	10.40	0.88	9.14	0.63	14.90	1.89	1.79
81-90	0.66	11.20	1.06	10.60	0.82	9.20	0.63	16.00	1.77	1.85
91-100	0.66	11.30	1.02	10.60	0.80	9.05	0.63	14.90	1.73	1.91
101-110	0.66	11.70	1.02	10.90	0.80	9.36	0.63	16.00	1.73	1.88
111-120	0.66	11.40	1.05	10.80	0.81	9.42	0.63	16.00	1.76	1.84
121-130	0.65	11.90	0.96	11.00	0.77	9.40	0.63	14.90	1.67	1.91
131-140	0.65	10.90	0.94	10.40	0.76	8.95	0.63	13.80	1.65	1.89
141-150	0.65	11.10	0.90	10.70	0.74	9.08	0.63	16.00	1.61	1.96
151-160	0.64	9.19	0.82	9.29	0.71	7.41	0.63	17.20	1.50	2.18
161-170	0.64	11.20	0.86	10.60	0.73	8.88	0.63	14.90	1.56	2.04
171-180	0.65	11.20	0.98	10.70	0.77	9.28	0.63	14.90	1.7	1.85
181-190	0.65	10.50	1.02	10.10	0.79	8.67	0.63	16.00	1.74	1.89
191-200	0.65	11.60	1.09	11.00	0.82	9.66	0.63	16.00	1.82	1.81
201-210	0.66	11.90	1.17	11.40	0.85	10.10	0.63	17.20	1.89	1.76
211-220	0.67	11.90	1.28	11.30	0.90	10.00	0.63	16.00	1.98	1.73
221-230	0.65	11.40	1.11	10.90	0.83	9.49	0.63	17.20	1.84	1.81
231-240	0.65	11.90	1.06	11.20	0.80	9.86	0.63	17.20	1.79	1.79
241-250	0.66	12.30	1.16	11.50	0.83	10.30	0.63	16.00	0.83	10.3
251-260	0.65	12.00	1.02	11.40	0.78	10.00	0.63	17.20	1.75	1.80
261-270	1.25	11.60	2.33	11.30	1.51	10.20	0.63	16.00	2.42	1.65
271-280	0.84	11.80	1.94	11.30	1.25	10.20	0.63	14.90	2.33	1.66
281-290	0.81	11.50	1.82	11.10	1.20	9.87	0.63	14.90	2.26	1.70
291-300	0.78	11.10	1.72	10.90	1.15	9.65	0.63	16.00	2.22	1.72
301-310	0.80	12.20	1.81	11.40	1.19	10.20	0.63	14.90	2.26	1.69
311-320	0.78	9.15	1.08	9.34	0.90	7.72	0.72	17.20	1.63	2.03
321-330	0.79	10.20	1.22	10.00	0.96	8.57	0.67	13.80	1.78	1.88
331-340	0.79	8.72	0.93	8.74	0.85	6.51	0.72	14.90	1.43	2.47
341-350	0.82	10.94	1.18	9.53	0.94	9.21	0.71	14.40	1.82	2.01
351-360	0.84	11.31	0.99	10.13	0.99	8.79	0.77	15.30	1.91	2.19
Avg	0.71	11.24	1.21	10.75	0.89	9.34	0.64	15.79	1.81	2.11
SD	0.11	0.86	0.34	0.65	0.17	0.84	0.03	1.09	0.29	1.48

Data for Chapter 5

Table B-3 Removal efficiencies for airborne particles of the charged and uncharged water sprays.

Powder	Method	Polarity	Removal efficiency (%)			
			TSP	≤10μm	≤2.5μm	≤1μm
Corn Starch	Charged spray (4 min spray duration)	Positive	98.1	90.6	47.4	56.2
	Charged spray (High RH, 4 min spray duration)		-	86.9	3.2	43.2
	Charged spray (Intermittent, 4 min spray duration)		98.5	93.1	59.5	-
	Charged spray (6 min spray duration)	Negative	98.4	92.2	19.3	-
	Charged spray (2 min spray duration)		96.8	83.9	18	-
	Charged spray (4 min spray duration)		98.1	92.6	37.6	48.2
	Uncharged spray (4 min spray duration)	Uncharged	89.2	62.3	0.76	-
	No spray	-	84.8	52.8	28.4	55.6
NaHCO ₃	Charged spray (4 min spray duration)	Positive	93.7	82.9	65.7	44.8
	Charged spray (High RH, 4 min spray duration)		-	83.3	61	38
	Charged spray (Intermittent, 4 min spray duration)		95.6	88.9	73.7	-
	Charged spray (6 min spray duration)	Negative	95.7	89.1	74.5	-
	Charged spray (2 min spray duration)		93.2	76.1	61.3	-
	Charged spray (4 min spray duration)		94	91.1	74.8	49
	Uncharged spray (4 min spray duration)	Uncharged	64.4	31.1	0.35	-
	No spray	-	55.8	37.3	27.9	25

Table B-4 Removal efficiencies for total suspended airborne particles (TSP) based on mass concentration (20g nominal amount deployed).

Powder	Method	Polarity	Removal efficiency (%)					
			R1	R2	R3	R4	Mean	SD
Corn Starch	Charged spray (4 min spray duration)	Positive	92.66	92.08	96.40	-	93.7	2.3
	Charged spray (Intermittent, 4 min spray duration)		96.67	94.92	95.60	-	95.7	0.9
	Charged spray (6 min spray duration)	Negative	93.82	95.10	93.43	-	94.1	0.9
	Charged spray (2 min spray duration)		88.66	95.66	92.15	-	92.2	3.5
	Charged spray (4 min spray duration)		96.33	93.23	88.19	-	92.6	4.1
	Uncharged spray (4 min spray duration)	Uncharged	91.94	90.12	91.40	-	91.2	0.9
	No spray	-	90.57	88.19	88.36	91.29	89.0	1.3
NaHCO ₃	Charged spray (4 min spray duration)	Positive	93.45	93.66	89.42	-	92.2	2.4
	Charged spray (Intermittent, 4 min spray duration)		93.5	91.2	94.1	-	92.9	1.5
	Charged spray (6 min spray duration)	Negative	95.2	93.1	0.0	-	62.8	54.4
	Charged spray (2 min spray duration)		91.9	94.8	93.4	-	93.4	1.4
	Charged spray (4 min spray duration)		85.8	95.1	89.4	-	90.1	4.7
	Uncharged spray (4 min spray duration)	Uncharged	78.6	74.3	-	-	76.5	3.1
	No spray	-	71.1	76.2	67.3	-	71.5	4.5

Table B-5 Removal efficiencies for airborne particles (0.54-10 μm) based on number and mass concentration (20g nominal amount deployed).

Powder	Method	Polarity	Removal efficiency (%)			
			Number concentration		Mass concentration	
			Mean	SD	Mean	SD
Corn Starch	Charged spray (4 min spray duration)	Positive	52.91	5.64	90.6	7.1
	Charged spray (High RH, 4 min spray duration)		17.85	3.08	86.9	2.2
	Charged spray (Intermittent, 4 min spray duration)	Negative	53.15	17.09	93.1	3.9
	Charged spray (6 min spray duration)		24.99	2.46	92.2	1.8
	Charged spray (2 min spray duration)		28.48	5.97	83.9	2.1
	Charged spray (4 min spray duration)		31.34	7.48	91.7	1.8
	Uncharged spray (4 min spray duration)	Uncharged	15.27	6.37	62.3	6.8
	No spray	-	31.23	6.48	52.8	4.0
NaHCO_3	Charged spray (4 min duration)	Positive	68.30	1.81	83.1	2.2
	Charged spray (High RH, 4 min spray duration)		60.32	4.61	83.3	4.3
	Charged spray (Intermittent, 4 min spray duration)	Negative	72.23	2.93	89.0	2.6
	Charged spray (6 min spray duration)		75.59	4.01	89.1	3.7
	Charged spray (2 min spray duration)		60.55	1.83	76.1	5.2
	Charged spray (4 min spray duration)		68.23	7.09	87.7	3.2
	Uncharged spray (4 min spray duration)	Uncharged	0.98	0.74	31.1	5.9
	No spray	-	28.73	1.36	37.5	4.4

Table B-6 Removal efficiencies for airborne particles (0.54-10 µm) based on mass concentration (20g nominal amount deployed).

Powder	Method	Polarity	Removal efficiency (%)								
			R1	R2	R3	R4	R5	R6	Mean	SD	
Corn Starch	Charged spray (4 min spray duration)	Positive	90.0	83.7	98.0	-	-	-	90.6	7.1	
	Charged spray (High RH, 4 min spray duration)		85.3	86.1	89.5	-	-	-	86.9	2.2	
	Charged spray (Intermittent, 4 min spray duration)		97.6	90.5	91.2	-	-	-	93.1	3.9	
	Charged spray (6 min spray duration)		93.7	92.8	90.2	-	-	-	92.2	1.8	
	Charged spray (2 min spray duration)		81.6	85.7	84.2	-	-	-	83.9	2.1	
	Charged spray (4 min spray duration)	Negative	90.3	91.6	94.2	90.8	-	-	91.7	1.8	
	Uncharged spray (4 min spray duration)		Uncharged	55.0	68.4	63.6	-	-	-	62.3	6.8
	No spray			-	53.0	48.8	56.7	-	-	-	52.8
NaHCO ₃	Charged spray (4 min duration)	Positive	82.3	81.5	85.6	-	-	-	83.1	2.2	
	Charged spray (High RH, 4 min spray duration)		80.3	81.4	88.2	-	-	-	83.3	4.3	
	Charged spray (Intermittent, 4 min spray duration)		89.7	91.1	86.1	-	-	-	89.0	2.6	
	Charged spray (6 min spray duration)		92.1	84.9	90.3	-	-	-	89.1	3.7	
	Charged spray (2 min spray duration)		78.3	70.1	79.9	-	-	-	76.1	5.2	
	Charged spray (4 min spray duration)	Negative	92.9	90.3	86.0	86.5	85.2	85.5	87.7	3.2	
	Uncharged spray (4 min spray duration)		Uncharged	36.1	24.7	32.6	-	-	-	31.1	5.9
	No spray			-	32.4	40.7	35.2	41.6	-	-	37.5

Table B-7 Removal efficiencies for airborne particles (0.54-10 μm) based on number and mass concentration (10g nominal amount deployed).

Powder	Method	Polarity	Removal efficiency (%)			
			Number concentration		Mass concentration	
			Mean	SD	Mean	SD
Corn Starch	Charged spray (4 min spray duration)	Negative	18.22	4.13	90.38	3.75
	No spray	-	36.72	8.65	49.00	7.00
NaHCO ₃	Charged spray (4 min spray duration)	Negative	62.53	1.65	80.50	2.36
	No spray	-	22.54	1.85	39.86	6.24

Table B-8 Removal efficiencies for airborne particles (0.54-10 μm) based on number and mass concentration (10g nominal amount deployed).

Powder	Method	Polarity	Removal efficiency (%)					
			R1	R2	R3	R4	Mean	SD
Corn Starch	Charged spray (4 min spray duration)	Negative	86.53	91.61	94.83	86.16	89.8	4.2
	No spray	-	40.76	46.29	57.17	53.20	49.4	7.3
NaHCO ₃	Charged spray (4 min spray duration)	Negative	78.83	82.18	79.68	-	80.2	1.7
	No spray	-	41.49	32.96	45.12	-	39.9	6.2

Table B-9 Removal efficiencies for airborne particles (0.54-10 μm) based on number and mass concentration (30g nominal amount deployed).

Powder	Method	Polarity	Removal efficiency (%)			
			Number concentration		Mass concentration	
			Mean	SD	Mean	SD
Corn Starch	Charged spray (4 min spray duration)	Negative	48.54	10.85	90.66	3.96
	No spray	-	21.70	16.48	51.03	1.70
NaHCO ₃	Charged spray (4 min spray duration)	Negative	68.66	4.14	86.23	2.29
	No spray	-	38.04	13.78	51.04	17.10

Table B-10 Removal efficiencies for airborne particles (0.54-10 μm) based on number and mass concentration (30g nominal amount deployed).

Powder	Method	Polarity	Removal efficiency (%)				
			R1	R2	R3	Mean	SD
Corn Starch	Charged spray (4 min spray duration)	Negative	86.19	92.07	93.73	90.7	4.0
	No spray	-	49.85	52.20	-	51.0	1.7
NaHCO ₃	Charged spray (4 min spray duration)	Negative	83.90	88.47	86.33	86.2	2.3
	No spray	-	52.27	33.36	67.48	51.0	17.1

Table B-11 Removal efficiencies for airborne particles (0.54-2.5 μm) based on number and mass concentration (20g nominal amount deployed).

Powder	Method	Polarity	Removal efficiency (%)			
			Number concentration		Mass concentration	
			Mean	SD	Mean	SD
Corn Starch	Charged spray (4 min spray duration)	Positive	41.77	3.36	47.39	3.77
	Charged spray (High RH, 4 min spray duration)		9.19	1.94	3.20	2.73
	Charged spray (Intermittent, 4 min spray duration)	Negative	40.56	15.86	59.54	20.17
	Charged spray (6 min spray duration)		10.11	1.78	19.30	10.92
	Charged spray (2 min spray duration)		18.14	6.65	22.89	7.32
	Charged spray (4 min spray duration)		16.91	11.36	33.48	8.47
	Uncharged spray (4 min spray duration)	Uncharged	0.10	0.17	0.76	1.32
	No spray	-	29.42	6.63	28.35	6.52
NaHCO ₃	Charged spray (4 min duration)	Positive	67.92	1.93	65.69	2.73
	Charged spray (High RH, 4 min spray duration)		59.61	4.52	61.01	5.62
	Charged spray (Intermittent, 4 min spray duration)	Negative	71.52	2.96	73.65	3.43
	Charged spray (6 min spray duration)		10.11	1.78	74.53	4.68
	Charged spray (2 min spray duration)		60.01	1.62	61.23	3.55
	Charged spray (4 min spray duration)		67.46	7.32	69.53	7.50
	Uncharged spray (4 min spray duration)	Uncharged	0.25	0.44	0.35	0.61
	No spray	-	28.66	1.49	27.91	1.31

Table B-12 Removal efficiencies for airborne particles (0.54-2.5 μm) based on mass concentration (20g nominal amount deployed).

Powder	Method	Polarity	Removal efficiency (%)							
			R1	R2	R3	R4	R5	R6	Mean	SD
Corn Starch	Charged spray (4 min spray duration)	Positive	49.4	43.0	49.8	-	-	-	47.4	3.8
	Charged spray (High RH, 4 min spray duration)		5.7	0.3	3.6	-	-	-	3.2	2.7
	Charged spray (Intermittent, 4 min spray duration)	Negative	82.1	53.2	43.3	-	-	-	59.5	20.2
	Charged spray (6 min spray duration)		18.7	30.5	8.7	-	-	-	19.3	10.9
	Charged spray (2 min spray duration)		28.1	17.7	22.9	-	-	-	22.9	5.3
	Charged spray (4 min spray duration)		45.6	26.2	32.4	29.7	-	-	33.5	8.5
	Uncharged spray (4 min spray duration)	Uncharged	2.3	0.0	0.0	-	-	-	0.8	1.3
	No spray	-	35.4	22.6	27.1	-	-	-	28.4	6.5
NaHCO ₃	Charged spray (4 min duration)	Positive	67.9	67.6	65.3	62.0	-	-	65.7	2.7
	Charged spray (High RH, 4 min spray duration)		57.3	58.2	67.5	-	-	-	61.0	5.6
	Charged spray (Intermittent, 4 min spray duration)	Negative	73.9	76.9	70.1	-	-	-	73.6	3.4
	Charged spray (6 min spray duration)		79.8	70.8	73.0	-	-	-	74.5	4.7
	Charged spray (2 min spray duration)		61.2	57.7	64.8	-	-	-	61.2	3.6
	Charged spray (4 min spray duration)		79.5	75.5	69.6	68.4	58.0	66.1	69.5	7.5
	Uncharged spray (4 min spray duration)	Uncharged	1.1	0.0	0.0	-	-	-	0.4	0.6
	No spray	-	28.9	26.0	28.6	-	-	-	27.8	1.6

Table B-13 Removal efficiencies for submicron particles (20-835 nm) based on mass concentration (20g nominal amount deployed).

Powder	Method	Polarity	Removal efficiency (%)				
			R1	R2	R3	Mean	SD
Corn Starch	Charged spray (4 min spray duration)	Positive	45.54	70.38	52.62	56.2	12.8
	Charged spray ((High RH, 4 min spray duration)	Negative	45.29	34.55	49.64	43.2	7.8
	Charged spray (4 min spray duration)		39.63	68.52	36.58	48.2	17.6
	No spray	-	62.18	78.35	26.28	55.6	26.7
NaHCO ₃	Charged spray (4 min spray duration)	Positive	57.41	27.68	49.38	44.8	15.4
	Charged spray ((High RH, 4 min spray duration)	Negative	40.5	41.1	32.4	38.0	4.9
	Charged spray (4 min spray duration)		37.88	58.85	50.15	49.0	10.5
	No spray	-	18.7	32.0	24.4	25.0	6.7

Data for Chapter 6

Table B-14 Values of K_{exp} as a function of time for total dust concentration for the negatively-charged water spray treatment on corn starch.

Time (min)	Rep 1			Rep 2				Rep 3				Avg. measured conc. mg/m ³	K_{exp}	
	Measured	Calculated	Predicted	Predicted	Measured	Calculated	Predicted	Predicted	Measured	Calculated	Predicted			Predicted
	conc. mg/m ³	eff. %	eff. %	conc. mg/m ³	conc. mg/m ³	eff. %	eff. %	conc. mg/m ³	conc. mg/m ³	eff. %	eff. %			conc. mg/m ³
0	348.94	0.00	0.00	348.94	210.12	0.00	0.00	210.12	132.59	0.00	0.00	132.59	230.55	0.00E+00
1	190.89	45.30	53.91	160.82	105.70	49.69	41.33	78.05	63.48	52.12	30.77	52.34	120.02	5.59E-05
2	135.63	61.13	75.55	70.95	79.55	62.14	65.04	46.67	33.15	75.00	54.01	25.63	82.78	7.38E-05
3	117.17	66.42	86.82	38.09	63.86	69.61	79.87	28.95	18.34	86.17	71.46	13.63	66.46	1.05E-04
4	74.55	78.64	92.38	23.11	66.24	68.48	87.95	20.07	12.05	90.91	82.16	8.49	50.95	1.45E-04
5	40.15	88.50	95.78	12.74	42.48	79.78	93.19	11.28	5.26	96.03	89.62	3.92	29.30	2.17E-04
6	23.03	93.40	97.53	7.25	27.78	86.78	95.96	6.71	3.43	97.41	93.75	2.47	18.08	3.14E-04
7	13.85	96.03	98.53	4.25	21.12	89.95	97.58	4.18	2.71	97.96	96.22	1.78	12.56	4.56E-04
8	8.81	97.48	98.82	3.21	14.16	93.26	98.05	3.22	2.02	98.48	96.95	1.36	8.33	4.99E-04
9	7.50	97.85	98.92	2.66	8.82	95.80	98.22	2.66	1.45	98.91	97.21	1.05	5.92	4.86E-04
10	6.68	98.09	99.03	2.35	6.94	96.70	98.40	2.29	1.97	98.51	97.49	1.25	5.20	4.88E-04
11	6.33	98.19	99.35	1.71	5.75	97.26	98.92	1.64	1.24	99.06	98.30	0.81	4.44	6.61E-04
12	5.24	98.50	99.18	1.98	5.27	97.49	98.65	1.86	2.09	98.42	97.87	1.21	4.20	4.82E-04
13	5.01	98.56	99.21	1.82	4.92	97.66	98.69	1.78	1.72	98.70	97.94	1.06	3.89	4.60E-04
14	5.02	98.56	99.51	1.27	4.40	97.91	99.20	1.23	1.05	99.21	98.73	0.65	3.49	6.99E-04
15	4.19	98.80	99.42	1.45	4.07	98.06	99.04	1.36	1.23	99.07	98.49	0.77	3.16	5.45E-04
16	4.22	98.79	99.56	1.12	4.84	97.70	99.28	1.17	1.09	99.18	98.86	0.64	3.38	6.79E-04
17	3.49	99.00	99.61	1.03	3.57	98.30	99.36	0.98	0.74	99.45	98.99	0.48	2.60	7.23E-04
18	3.68	98.95	99.65	0.91	3.38	98.39	99.42	0.90	0.39	99.70	99.09	0.30	2.49	7.56E-04
19	3.22	99.08	99.61	0.99	3.48	98.34	99.36	0.98	0.84	99.37	98.99	0.52	2.51	6.46E-04
20	4.01	98.85	99.68	0.83	3.07	98.54	99.48	0.82	0.31	99.77	99.17	0.24	2.47	7.52E-04
21	3.08	99.12	99.74	0.74	2.33	98.89	99.57	0.65	0.00	100.00	99.32	0.00	1.81	8.74E-04
22	3.26	99.07	99.66	0.86	1.95	99.07	99.43	0.74	0.46	99.65	99.10	0.33	1.89	6.31E-04
23	2.64	99.24	99.79	0.60	2.76	98.69	99.65	0.58	0.02	99.98	99.45	0.02	1.81	9.94E-04
24	2.98	99.15	99.76	0.63	4.60	97.81	99.60	0.71	0.24	99.82	99.38	0.19	2.61	8.32E-04
25	2.79	99.20	99.78	0.60	1.98	99.06	99.64	0.55	-0.28	100.21	99.43	-0.44	1.50	8.79E-04
26	3.10	99.11	99.68	0.80	1.96	99.07	99.47	0.71	0.78	99.41	99.16	0.46	1.95	5.72E-04
27	2.74	99.21	99.70	0.79	2.34	98.89	99.50	0.73	0.23	99.83	99.20	0.19	1.77	5.79E-04
28	2.59	99.26	99.72	0.73	0.83	99.61	99.53	0.45	0.89	99.33	99.26	0.47	1.44	6.03E-04
29	2.48	99.29	99.89	0.35	2.22	98.94	99.81	0.34	-0.32	100.24	99.70	-1.50	1.46	1.44E-03
30	2.48	99.29	99.82	0.50	1.73	99.18	99.70	0.46	0.15	99.89	99.53	0.12	1.45	0.001

Table B-15 Values of K_{exp} as a function of time for total dust concentration for the no-water spray treatment on corn starch.

Time (min)	Rep 1				Rep 2				Rep 3				Avg. measured conc. mg/m ³	K_{exp}
	Measured conc.	Calculated eff.	Predicted eff.	Predicted conc.	Measured conc.	Calculated eff.	Predicted eff.	Predicted conc.	Measured conc.	Calculated eff.	Predicted eff.	Predicted conc.		
0	149.03	0.00	0.00	149.03	131.60	0.00	0.00	131.60	210.74	0.00	0.00	210.74	166.82	0.000E+00
1	87.70	41.16	25.90	72.74	129.87	1.31	23.59	99.55	152.36	27.70	33.08	112.25	119.91	3.909E-05
2	75.20	49.54	41.90	55.14	94.75	28.00	38.91	64.96	115.85	45.03	50.49	74.23	92.30	4.033E-05
3	48.66	67.35	55.86	34.44	74.65	43.28	52.77	45.69	85.67	59.35	64.15	49.59	69.04	4.717E-05
4	44.47	70.16	60.74	30.42	54.19	58.82	57.74	34.68	84.12	60.09	68.63	44.90	61.06	4.326E-05
5	34.47	76.87	67.27	23.36	45.10	65.73	64.48	27.80	71.12	66.25	74.40	35.90	50.54	4.598E-05
6	29.19	80.41	70.78	19.80	40.85	68.96	68.14	24.55	68.60	67.45	77.40	32.43	44.95	4.515E-05
7	24.71	83.42	74.21	16.73	36.11	72.56	71.76	21.27	60.89	71.11	80.28	27.98	39.52	4.598E-05
8	23.37	84.32	78.16	14.97	31.27	76.24	75.96	17.86	50.62	75.98	83.50	22.85	33.33	5.002E-05
9	20.22	86.43	81.37	12.70	26.50	79.86	79.41	14.92	41.58	80.27	86.06	18.74	28.33	5.426E-05
10	16.15	89.16	83.16	10.52	23.72	81.98	81.35	13.28	39.72	81.15	87.48	17.15	25.55	5.524E-05
11	14.29	90.41	85.47	9.14	20.72	84.26	83.85	11.40	33.11	84.29	89.27	14.35	22.00	5.980E-05
12	12.53	91.59	87.25	7.95	17.73	86.53	85.80	9.77	28.55	86.45	90.64	12.35	19.26	6.378E-05
13	11.55	92.25	88.06	7.35	16.05	87.81	86.69	8.94	28.65	86.41	91.25	11.85	18.02	6.345E-05
14	10.40	93.02	89.20	6.60	14.03	89.34	87.94	7.89	26.61	87.37	92.11	10.76	16.29	6.595E-05
15	9.93	93.34	90.54	6.06	13.32	89.88	89.42	7.18	22.41	89.36	93.12	9.19	14.24	7.135E-05
16	7.93	94.68	91.17	5.12	12.58	90.44	90.12	6.72	21.99	89.57	93.59	8.71	13.28	7.220E-05
17	7.58	94.92	91.86	4.81	11.12	91.55	90.88	6.04	20.60	90.22	94.10	8.05	12.24	7.424E-05
18	7.38	95.05	92.68	4.54	9.81	92.55	91.79	5.35	17.83	91.54	94.71	7.09	10.99	7.871E-05
19	6.23	95.82	93.55	3.88	9.52	92.77	92.76	4.94	14.86	92.95	95.35	6.08	9.68	8.534E-05
20	6.66	95.53	94.80	3.67	8.72	93.37	94.15	4.22	8.89	95.78	96.27	4.26	7.79	1.019E-04
21	5.89	96.05	95.48	3.21	7.92	93.98	94.91	3.73	6.10	97.11	96.76	3.27	6.78	1.124E-04
22	5.37	96.39	96.16	2.82	7.44	94.34	95.67	3.31	3.85	98.17	97.25	2.34	5.75	1.273E-04
23	5.05	96.61	96.57	2.59	6.89	94.76	96.13	3.00	2.57	98.78	97.55	1.73	5.14	1.367E-04
24	4.57	96.94	96.95	2.32	6.05	95.41	96.55	2.64	2.19	98.96	97.82	1.49	4.57	1.479E-04
25	4.24	97.16	96.93	2.23	5.80	95.60	96.53	2.60	3.09	98.53	97.81	1.87	4.60	1.411E-04
26	4.25	97.15	97.13	2.16	5.52	95.80	96.76	2.45	2.48	98.82	97.95	1.59	4.30	1.453E-04
27	3.77	97.47	97.50	1.90	4.57	96.53	97.18	2.08	1.76	99.17	98.22	1.20	3.74	1.614E-04
28	3.36	97.74	97.88	1.65	3.62	97.25	97.60	1.71	1.79	99.15	98.49	1.15	3.17	1.840E-04
29	2.92	98.04	98.08	1.46	3.32	97.48	97.83	1.55	1.17	99.45	98.63	0.83	2.87	1.966E-04
30	2.78	98.13	98.19	1.38	3.25	97.53	97.95	1.49	1.12	99.47	98.71	0.80	2.71	2.019E-04

Table B-16 Values of K_{exp} as a function of time for total dust concentration for the negatively-charged water spray treatment on $NaHCO_3$.

Time (min)	Rep 1				Rep 2				Rep 3				Avg. measured conc. mg/m ³	K_{exp}
	Measured conc.	Calculated eff.	Predicted eff.	Predicted conc.	Measured conc.	Calculated eff.	Predicted eff.	Predicted conc.	Measured conc.	Calculated eff.	Predicted eff.	Predicted conc.		
0	137.02	0.00	0.00	137.02	225.00	0.00	0.00	225.00	30.49	0.00	0.00	30.49	130.84	0.000E+00
1	119.17	13.03	46.39	73.46	76.60	65.96	58.69	51.63	19.18	37.10	16.14	17.11	71.65	1.052E-04
2	79.55	41.94	57.84	54.34	72.23	67.90	69.26	41.92	18.13	40.52	23.39	15.35	56.64	8.344E-05
3	43.12	68.53	76.11	27.92	37.13	83.50	83.95	19.93	16.87	44.67	41.48	12.12	32.37	1.292E-04
4	31.75	76.83	81.71	17.92	27.87	87.62	88.00	14.60	14.93	51.03	49.85	10.04	24.85	1.358E-04
5	24.14	82.39	86.00	13.10	22.86	89.84	90.98	11.29	10.20	66.55	57.74	7.00	19.06	1.494E-04
6	14.58	89.36	91.00	8.68	13.38	94.05	94.32	6.74	8.90	70.81	69.22	5.37	12.29	2.048E-04
7	12.17	91.12	93.34	5.85	8.92	96.04	95.84	4.66	6.19	79.70	75.73	3.79	9.09	2.436E-04
8	10.99	91.98	94.53	4.80	7.49	96.67	96.59	3.85	3.97	86.98	79.35	2.65	7.48	2.625E-04
9	10.58	92.28	95.10	4.30	7.34	96.74	96.96	3.60	2.19	92.80	81.18	1.67	6.71	2.621E-04
10	9.51	93.06	95.32	4.11	7.32	96.75	97.10	3.50	2.35	92.28	81.94	1.74	6.39	2.480E-04
11	9.00	93.43	95.59	3.80	6.96	96.91	97.27	3.31	2.13	93.02	82.83	1.59	6.03	2.398E-04
12	9.14	93.33	95.61	3.70	6.67	97.04	97.28	3.24	2.19	92.82	82.90	1.62	6.00	2.209E-04
13	8.72	93.63	95.76	3.65	6.33	97.19	97.37	3.10	2.37	92.24	83.39	1.70	5.80	2.111E-04
14	9.20	93.29	96.01	3.45	5.28	97.65	97.53	2.74	1.91	93.74	84.24	1.43	5.46	2.088E-04
15	8.25	93.98	96.13	3.45	5.55	97.54	97.61	2.77	2.09	93.14	84.67	1.52	5.30	2.013E-04
16	8.40	93.87	96.13	3.31	5.69	97.47	97.60	2.80	1.81	94.06	84.66	1.36	5.30	1.886E-04
17	8.17	94.04	96.25	3.27	5.04	97.76	97.68	2.59	2.20	92.78	85.08	1.56	5.14	1.834E-04
18	5.78	95.78	96.85	2.89	4.80	97.87	98.06	2.31	2.37	92.24	87.24	1.55	4.31	2.076E-04
19	5.59	95.92	97.05	2.42	4.70	97.91	98.18	2.21	1.83	93.99	87.97	1.27	4.04	2.105E-04
20	7.16	94.77	96.74	2.53	4.26	98.11	97.99	2.22	1.95	93.61	86.85	1.37	4.46	1.806E-04
21	7.42	94.58	96.61	2.88	4.71	97.91	97.91	2.38	1.78	94.18	86.39	1.30	4.63	1.652E-04
22	6.14	95.52	97.15	2.61	3.57	98.41	98.25	1.89	1.97	93.55	88.37	1.32	3.90	1.887E-04
23	7.28	94.69	96.74	2.64	4.09	98.18	97.99	2.17	2.00	93.44	86.86	1.40	4.46	1.571E-04
24	6.79	95.05	96.82	2.78	4.46	98.02	98.04	2.24	1.80	94.10	87.14	1.29	4.35	1.544E-04
25	5.67	95.86	97.37	2.40	3.52	98.44	98.38	1.80	1.62	94.70	89.17	1.13	3.60	1.800E-04
26	5.60	95.91	97.36	2.24	3.46	98.46	98.38	1.79	1.77	94.20	89.15	1.20	3.61	1.728E-04
27	5.34	96.10	97.61	2.10	2.92	98.70	98.53	1.56	1.58	94.82	90.07	1.07	3.28	1.836E-04
28	5.68	95.86	97.28	2.23	3.48	98.45	98.32	1.83	2.02	93.36	88.82	1.33	3.73	1.552E-04
29	4.32	96.85	97.74	2.04	3.28	98.54	98.61	1.61	1.68	94.48	90.58	1.10	3.10	1.812E-04
30	3.72	97.29	97.94	1.73	3.56	98.42	98.74	1.59	1.19	96.11	91.37	0.84	2.82	1.928E-04

Table B-17 Values of K_{exp} as a function of time for total dust concentration for the no-water-spray treatment on $NaHCO_3$.

Time (min)	Rep 1				Rep 2				Rep 3				Avg. measured conc. mg/m ³	K_{exp}
	Measured conc.	Calculated eff.	Predicted eff.	Predicted conc.	Measured conc.	Calculated eff.	Predicted eff.	Predicted conc.	Measured conc.	Calculated eff.	Predicted eff.	Predicted conc.		
0	67.38	0.00	0.00	67.38	134.31	0.00	0.00	134.31	125.15	0.00	0.00	125.15	108.95	0.000E+00
1	47.46	29.56	10.44	43.86	110.22	17.94	18.86	92.56	117.30	6.27	17.81	97.51	91.66	2.885E-05
2	40.56	39.81	16.40	36.27	100.64	25.07	28.12	77.83	106.92	14.57	26.71	81.53	82.70	2.427E-05
3	37.67	44.08	23.06	32.27	90.72	32.46	37.40	64.63	91.76	26.68	35.76	65.16	73.38	2.471E-05
4	37.93	43.71	26.19	31.61	83.33	37.95	41.43	57.91	86.41	30.96	39.73	59.38	69.22	2.195E-05
5	34.59	48.67	30.81	28.15	77.04	42.64	47.02	51.05	78.40	37.36	45.27	51.64	63.34	2.203E-05
6	33.27	50.61	36.53	25.91	67.71	49.58	53.43	42.90	68.29	45.44	51.67	43.13	56.43	2.373E-05
7	31.72	52.93	37.10	24.82	67.74	49.57	54.04	42.52	67.85	45.79	52.28	42.57	55.77	2.084E-05
8	29.40	56.37	40.47	22.67	60.58	54.89	57.54	37.60	65.71	47.50	55.81	39.51	51.90	2.102E-05
9	29.21	56.64	41.07	22.43	60.11	55.24	58.15	37.06	64.33	48.60	56.42	38.62	51.22	1.916E-05
10	28.00	58.44	43.41	21.23	59.13	55.97	60.46	35.34	58.76	53.05	58.76	35.21	48.63	1.897E-05
11	26.90	60.08	45.12	20.25	58.28	56.61	62.11	34.06	55.13	55.95	60.43	32.96	46.77	1.849E-05
12	25.62	61.97	47.08	19.15	53.15	60.43	63.94	31.23	55.27	55.84	62.30	31.95	44.68	1.834E-05
13	23.46	65.19	49.63	17.47	49.72	62.98	66.26	28.79	52.88	57.75	64.66	29.82	42.02	1.874E-05
14	23.39	65.29	51.01	17.18	48.40	63.97	67.49	27.69	50.00	60.05	65.92	28.20	40.60	1.840E-05
15	22.85	66.09	52.71	16.58	46.56	65.34	68.96	26.30	47.23	62.27	67.43	26.51	38.88	1.838E-05
16	22.13	67.16	55.01	15.79	43.11	67.90	70.91	24.19	44.53	64.42	69.43	24.63	36.59	1.891E-05
17	20.71	69.27	56.37	14.82	42.14	68.62	72.03	23.31	42.96	65.68	70.59	23.56	35.27	1.880E-05
18	19.29	71.36	57.28	13.94	41.15	69.36	72.78	22.62	42.71	65.87	71.36	23.09	34.38	1.843E-05
19	19.20	71.51	58.71	13.66	39.78	70.38	73.92	21.63	40.11	67.95	72.53	21.73	33.03	1.851E-05
20	18.85	72.02	59.33	13.39	38.77	71.14	74.41	21.08	39.70	68.28	73.04	21.35	32.44	1.804E-05
21	18.62	72.37	60.96	13.01	37.74	71.90	75.69	20.13	36.36	70.94	74.36	19.73	30.91	1.839E-05
22	17.27	74.37	61.80	12.21	36.48	72.84	76.33	19.45	36.64	70.72	75.03	19.49	30.13	1.819E-05
23	16.89	74.93	63.76	11.72	33.19	75.29	77.81	17.78	34.93	72.09	76.57	18.27	28.34	1.892E-05
24	16.08	76.13	63.98	11.29	33.50	75.06	77.98	17.79	34.84	72.17	76.74	18.16	28.14	1.831E-05
25	15.30	77.29	65.27	10.72	32.79	75.59	78.93	17.13	32.84	73.76	77.73	17.14	26.98	1.859E-05
26	15.52	76.97	66.16	10.70	32.06	76.13	79.58	16.61	30.97	75.25	78.41	16.31	26.18	1.860E-05
27	15.05	77.67	66.88	10.37	30.98	76.93	80.10	16.07	30.61	75.54	78.95	15.97	25.55	1.850E-05
28	13.48	79.99	68.16	9.44	30.26	77.47	81.01	15.43	29.52	76.41	79.90	15.23	24.42	1.891E-05
29	13.82	79.49	68.12	9.61	29.75	77.85	80.99	15.31	29.79	76.20	79.88	15.32	24.45	1.823E-05
30	13.61	79.80	70.11	9.23	26.55	80.23	82.38	13.80	28.04	77.60	81.33	14.19	22.73	1.934E-05

Table B-18 Predicted particle concentrations and removal efficiencies for total dust concentration as a function of time (Negatively charged water spray + Corn starch)

Time (min)	K _{exp}	Rep 1				Rep 2				Rep 3			
		Measured conc., mg/m ³	Predicted conc., mg/m ³	Calculated eff., %	Predicted eff., %	Measured conc., mg/m ³	Predicted conc., mg/m ³	Calculated eff., %	Predicted eff., %	Measured conc., mg/m ³	Predicted conc., mg/m ³	Calculated eff., %	Predicted eff., %
0	0.000E+00	348.94	348.94	0.00	0.00	210.12	210.12	0.00	0.00	132.59	132.59	0.00	0.00
1	5.587E-05	190.89	160.82	45.30	53.91	105.70	78.05	49.69	41.33	63.48	52.34	52.12	30.77
2	7.380E-05	135.63	70.95	61.13	75.55	79.55	46.67	62.14	65.04	33.15	25.63	75.00	54.01
3	1.049E-04	117.17	38.09	66.42	86.82	63.86	28.95	69.61	79.87	18.34	13.63	86.17	71.46
4	1.447E-04	74.55	23.11	78.64	92.38	66.24	20.07	68.48	87.95	12.05	8.49	90.91	82.16
5	2.170E-04	40.15	12.74	88.50	95.78	42.48	11.28	79.78	93.19	5.26	3.92	96.03	89.62
6	3.140E-04	23.03	7.25	93.40	97.53	27.78	6.71	86.78	95.96	3.43	2.47	97.41	93.75
7	4.564E-04	13.85	4.25	96.03	98.53	21.12	4.18	89.95	97.58	2.71	1.78	97.96	96.22
8	4.993E-04	8.81	3.21	97.48	98.82	14.16	3.22	93.26	98.05	2.02	1.36	98.48	96.95
9	4.860E-04	7.50	2.66	97.85	98.92	8.82	2.66	95.80	98.22	1.45	1.05	98.91	97.21
10	4.880E-04	6.68	2.35	98.09	99.03	6.94	2.29	96.70	98.40	1.97	1.25	98.51	97.49
11	6.612E-04	6.33	1.71	98.19	99.35	5.75	1.64	97.26	98.92	1.24	0.81	99.06	98.30
12	4.822E-04	5.24	1.98	98.50	99.18	5.27	1.86	97.49	98.65	2.09	1.21	98.42	97.87
13	4.603E-04	5.01	1.82	98.56	99.21	4.92	1.78	97.66	98.69	1.72	1.06	98.70	97.94
14	6.985E-04	5.02	1.27	98.56	99.51	4.40	1.23	97.91	99.20	1.05	0.65	99.21	98.73
15	5.453E-04	4.19	1.45	98.80	99.42	4.07	1.36	98.06	99.04	1.23	0.77	99.07	98.49
16	6.786E-04	4.22	1.12	98.79	99.56	4.84	1.17	97.70	99.28	1.09	0.64	99.18	98.86
17	7.231E-04	3.49	1.03	99.00	99.61	3.57	0.98	98.30	99.36	0.74	0.48	99.45	98.99
18	7.564E-04	3.68	0.91	98.95	99.65	3.38	0.90	98.39	99.42	0.39	0.30	99.70	99.09
19	6.458E-04	3.22	0.99	99.08	99.61	3.48	0.98	98.34	99.36	0.84	0.52	99.37	98.99
20	7.516E-04	4.01	0.83	98.85	99.68	3.07	0.82	98.54	99.48	0.31	0.24	99.77	99.17
21	8.740E-04	3.08	0.74	99.12	99.74	2.33	0.65	98.89	99.57	0.00	0.00	100.00	99.32
22	6.307E-04	3.26	0.86	99.07	99.66	1.95	0.74	99.07	99.43	0.46	0.33	99.65	99.10
23	9.942E-04	2.64	0.60	99.24	99.79	2.76	0.58	98.69	99.65	0.02	0.02	99.98	99.45
24	8.323E-04	2.98	0.63	99.15	99.76	4.60	0.71	97.81	99.60	0.24	0.19	99.82	99.38
25	8.794E-04	2.79	0.60	99.20	99.78	1.98	0.55	99.06	99.64	-0.28	-0.44	100.21	99.43
26	5.716E-04	3.10	0.80	99.11	99.68	1.96	0.71	99.07	99.47	0.78	0.46	99.41	99.16
27	5.790E-04	2.74	0.79	99.21	99.70	2.34	0.73	98.89	99.50	0.23	0.19	99.83	99.20
28	6.034E-04	2.59	0.73	99.26	99.72	0.83	0.45	99.61	99.53	0.89	0.47	99.33	99.26
29	1.443E-03	2.48	0.35	99.29	99.89	2.22	0.34	98.94	99.81	-0.32	-1.50	100.24	99.70
30	8.838E-04	2.48	0.50	99.29	99.82	1.73	0.46	99.18	99.70	0.15	0.12	99.89	99.53

Table B-19 Predicted particle concentrations and removal efficiencies for total dust concentration as a function of time (No water spray + Corn starch)

Time (min)	K _{exp}	Rep 1				Rep 2				Rep 3			
		Measured conc.	Predicted conc.	Calculated eff.	Predicted eff.	Measured conc.	Predicted conc.	Calculated eff.	Predicted eff.	Measured conc.	Predicted conc.	Calculated eff.	Predicted eff.
0	0.000E+00	396.23	396.23	0.00	0.00	650.94	650.94	0.00	0.00	175.93	175.93	0.00	0.00
1	3.909E-05	163.36	118.11	58.77	48.17	140.57	105.72	78.41	60.42	109.70	87.25	37.64	29.21
2	4.033E-05	121.95	76.69	69.22	65.73	96.47	65.76	85.18	75.91	83.40	59.42	52.60	45.99
3	4.717E-05	94.51	52.44	76.15	77.09	89.78	50.95	86.21	84.68	67.18	42.78	61.82	59.90
4	4.326E-05	81.45	44.13	79.45	80.45	73.12	41.57	88.77	87.11	61.48	37.53	65.06	64.62
5	4.598E-05	74.85	36.83	81.11	84.53	62.00	33.42	90.48	89.98	51.46	30.10	70.75	70.82
6	4.515E-05	60.70	30.55	84.68	86.56	55.13	29.08	91.53	91.37	41.14	24.66	76.61	74.09
7	4.598E-05	57.29	27.20	85.54	88.44	54.79	26.62	91.58	92.63	36.36	21.36	79.34	77.26
8	5.002E-05	50.97	22.92	87.14	90.49	49.30	22.58	92.43	93.99	28.05	16.76	84.05	80.86
9	5.426E-05	47.47	19.85	88.02	92.07	39.82	18.38	93.88	95.02	25.03	14.44	85.77	83.75
10	5.524E-05	41.49	17.47	89.53	92.92	36.88	16.59	94.34	95.57	22.62	12.93	87.14	85.36
11	5.980E-05	34.96	14.69	91.18	93.99	33.40	14.41	94.87	96.25	19.87	11.14	88.71	87.41
12	6.378E-05	32.54	13.05	91.79	94.79	29.93	12.60	95.40	96.76	18.24	9.92	89.64	88.99
13	6.345E-05	28.79	11.87	92.73	95.15	25.42	11.26	96.09	96.99	15.84	8.88	91.00	89.70
14	6.595E-05	23.75	10.26	94.01	95.64	23.38	10.19	96.41	97.30	14.11	7.92	91.98	90.70
15	7.135E-05	24.55	9.53	93.80	96.22	22.14	9.14	96.60	97.66	11.30	6.55	93.58	91.87
16	7.220E-05	22.52	8.79	94.32	96.49	19.86	8.36	96.95	97.83	10.62	6.12	93.97	92.42
17	7.424E-05	20.29	8.00	94.88	96.78	16.84	7.40	97.41	98.01	9.65	5.58	94.52	93.02
18	7.871E-05	19.42	7.33	95.10	97.12	16.28	6.83	97.50	98.23	8.94	5.08	94.92	93.73
19	8.534E-05	18.17	6.57	95.42	97.47	15.35	6.16	97.64	98.45	8.12	4.54	95.39	94.48
20	1.019E-04	17.33	5.56	95.63	97.98	14.14	5.18	97.83	98.76	6.90	3.74	96.08	95.56
21	1.124E-04	16.03	4.90	95.96	98.25	13.24	4.61	97.97	98.93	7.19	3.56	95.91	96.14
22	1.273E-04	15.57	4.31	96.07	98.52	12.28	4.01	98.11	99.09	6.32	3.06	96.41	96.73
23	1.367E-04	13.92	3.84	96.49	98.68	11.81	3.66	98.19	99.19	6.04	2.82	96.57	97.08
24	1.479E-04	13.51	3.49	96.59	98.83	10.61	3.26	98.37	99.28	5.47	2.53	96.89	97.40
25	1.411E-04	13.12	3.47	96.69	98.82	10.36	3.24	98.41	99.28	5.25	2.49	97.02	97.39
26	1.453E-04	12.16	3.24	96.93	98.90	9.71	3.03	98.51	99.33	4.94	2.33	97.19	97.55
27	1.614E-04	12.15	2.91	96.94	99.04	9.35	2.71	98.56	99.42	4.86	2.14	97.24	97.87
28	1.840E-04	10.77	2.49	97.28	99.19	8.86	2.37	98.64	99.51	3.92	1.77	97.77	98.20
29	1.966E-04	10.90	2.31	97.25	99.27	7.98	2.14	98.77	99.55	4.09	1.70	97.68	98.37
30	2.019E-04	10.50	2.18	97.35	99.31	7.97	2.05	98.78	99.58	3.68	1.57	97.91	98.46

Table B-20 Predicted particle concentrations and removal efficiencies for total dust concentration as a function of time (Negatively charged water spray+NaHCO₃)

Time (min)	K _{exp}	Rep 1				Rep 2				Rep 3			
		Measured conc.	Predicted conc.	Calculated eff.	Predicted eff.	Measured conc.	Predicted conc.	Calculated eff.	Predicted eff.	Measured conc.	Predicted conc.	Calculated eff.	Predicted eff.
0	0.000E+00	112.94	112.94	0.00	0.00	69.98	69.98	0.00	0.00	30.49	30.49	0.00	0.00
1	1.052E-04	64.65	65.93	42.75	41.63	58.49	42.71	16.43	30.65	19.18	17.11	37.10	16.14
2	8.344E-05	59.21	39.25	47.57	53.07	52.41	34.37	25.11	41.20	18.13	15.35	40.52	23.39
3	1.292E-04	56.76	24.92	49.75	72.42	51.11	23.36	26.96	61.93	16.87	12.12	44.67	41.48
4	1.358E-04	42.85	19.91	62.06	78.64	40.13	17.38	42.66	69.53	14.93	10.04	51.03	49.85
5	1.494E-04	30.11	14.67	73.34	83.50	29.38	12.68	58.02	75.82	10.20	7.00	66.55	57.74
6	2.048E-04	18.29	9.35	83.81	89.28	17.79	7.70	74.58	83.77	8.90	5.37	70.81	69.22
7	2.436E-04	13.24	6.37	88.28	92.04	11.56	5.30	83.49	87.75	6.19	3.79	79.70	75.73
8	2.625E-04	10.18	4.96	90.98	93.44	8.88	4.19	87.31	89.82	2.57	1.94	91.58	79.35
9	2.621E-04	8.09	4.17	92.84	94.11	7.35	3.60	89.50	90.83	2.19	1.67	92.80	81.18
10	2.480E-04	8.69	3.67	92.31	94.38	7.23	3.48	89.67	91.24	2.35	1.74	92.28	81.94
11	2.398E-04	8.78	3.66	92.22	94.70	6.84	3.28	90.23	91.72	2.13	1.59	93.02	82.83
12	2.209E-04	8.33	3.66	92.63	94.73	6.09	3.09	91.30	91.76	2.19	1.62	92.82	82.90
13	2.111E-04	8.29	3.51	92.66	94.90	6.42	3.12	90.82	92.01	2.37	1.70	92.24	83.39
14	2.088E-04	8.11	3.38	92.82	95.19	5.99	2.92	91.45	92.47	1.91	1.43	93.74	84.24
15	2.013E-04	7.63	3.28	93.24	95.34	5.92	2.86	91.54	92.69	2.09	1.52	93.14	84.67
16	1.886E-04	6.57	3.20	94.19	95.34	5.50	2.76	92.14	92.69	1.81	1.36	94.06	84.66
17	1.834E-04	7.47	2.95	93.38	95.48	5.39	2.68	92.30	92.91	2.20	1.56	92.78	85.08
18	2.076E-04	6.56	2.79	94.19	96.20	5.31	2.42	92.42	94.01	2.37	1.55	92.24	87.24
19	2.105E-04	6.50	2.55	94.25	96.44	4.96	2.26	92.92	94.38	1.83	1.27	93.99	87.97
20	1.806E-04	6.34	2.70	94.39	96.07	4.51	2.28	93.56	93.81	1.95	1.37	93.61	86.85
21	1.652E-04	6.18	2.73	94.53	95.92	4.37	2.29	93.76	93.58	1.78	1.30	94.18	86.39
22	1.887E-04	5.77	2.43	94.89	96.57	4.63	2.15	93.39	94.58	1.97	1.32	93.55	88.37
23	1.571E-04	5.94	2.56	94.74	96.08	4.53	2.29	93.53	93.82	2.00	1.40	93.44	86.86
24	1.544E-04	5.21	2.56	95.39	96.17	4.13	2.15	94.10	93.96	1.80	1.29	94.10	87.14
25	1.800E-04	5.15	2.16	95.44	96.83	4.43	2.02	93.67	94.97	1.62	1.13	94.70	89.17
26	1.728E-04	5.16	2.16	95.43	96.82	3.79	1.88	94.58	94.97	1.77	1.20	94.20	89.15
27	1.836E-04	5.25	2.04	95.35	97.11	4.05	1.84	94.22	95.42	1.58	1.07	94.82	90.07
28	1.552E-04	4.45	2.22	96.06	96.72	3.90	1.93	94.43	94.80	2.02	1.33	93.36	88.82
29	1.812E-04	4.43	1.85	96.08	97.27	3.95	1.76	94.36	95.66	1.68	1.10	94.48	90.58
30	1.928E-04	4.73	1.75	95.81	97.51	3.89	1.66	94.44	96.05	1.19	0.84	96.11	91.37

Table B-21 Predicted particle concentrations and removal efficiencies for total dust concentration as a function of time(Negatively charged water spray+NaHCO₃)

Time (min)	K _{exp}	Rep 1				Rep 2				Rep 3			
		Measured conc.	Predicted conc.	Calculated eff.	Predicted eff.	Measured conc.	Predicted conc.	Calculated eff.	Predicted eff.	Measured conc.	Predicted conc.	Calculated eff.	Predicted eff.
0	0.000E+00	398.30	398.30	0.00	0.00	67.38	67.38	0.00	0.00	124.45	124.45	0.00	0.00
1	2.885E-05	170.90	131.89	57.09	40.81	47.46	43.86	29.56	10.44	83.61	73.04	32.82	17.72
2	2.427E-05	131.52	95.09	66.98	53.70	40.56	36.27	39.81	16.40	66.14	55.46	46.86	26.60
3	2.471E-05	114.90	76.04	71.15	63.92	37.67	32.27	44.08	23.06	59.56	47.08	52.15	35.64
4	2.195E-05	100.37	65.66	74.80	67.72	37.93	31.61	43.71	26.19	51.81	40.70	58.37	39.60
5	2.203E-05	70.06	47.89	82.41	72.47	34.59	28.15	48.67	30.81	47.97	36.42	61.46	45.13
6	2.373E-05	70.06	43.83	82.41	77.29	33.27	25.91	50.61	36.53	43.24	31.58	65.26	51.53
7	2.084E-05	57.61	38.30	85.54	77.71	31.72	24.82	52.93	37.10	40.47	29.88	67.48	52.14
8	2.102E-05	54.62	35.21	86.29	80.08	29.40	22.67	56.37	40.47	37.63	27.27	69.77	55.67
9	1.916E-05	48.57	32.33	87.81	80.47	29.21	22.43	56.64	41.07	35.05	25.72	71.84	56.29
10	1.897E-05	41.04	27.97	89.70	81.93	28.00	21.23	58.44	43.41	32.20	23.56	74.13	58.62
11	1.849E-05	37.12	25.55	90.68	82.94	26.90	20.25	60.08	45.12	30.88	22.43	75.19	60.30
12	1.834E-05	33.14	23.05	91.68	84.02	25.62	19.15	61.97	47.08	30.36	21.67	75.60	62.17
13	1.874E-05	31.32	21.48	92.14	85.35	23.46	17.47	65.19	49.63	28.34	20.04	77.23	64.53
14	1.840E-05	28.17	19.62	92.93	86.03	23.39	17.18	65.29	51.01	26.97	19.04	78.33	65.79
15	1.838E-05	24.23	17.30	93.92	86.82	22.85	16.58	66.09	52.71	25.56	17.96	79.47	67.31
16	1.891E-05	22.55	16.00	94.34	87.85	22.13	15.79	67.16	55.01	24.18	16.81	80.57	69.32
17	1.880E-05	19.20	14.03	95.18	88.42	20.71	14.82	69.27	56.37	23.73	16.31	80.93	70.47
18	1.843E-05	15.87	12.06	96.02	88.80	19.29	13.94	71.36	57.28	22.32	15.45	82.07	71.24
19	1.851E-05	15.52	11.69	96.10	89.37	19.20	13.66	71.51	58.71	21.86	14.96	82.44	72.42
20	1.804E-05	14.44	11.00	96.38	89.61	18.85	13.39	72.02	59.33	21.09	14.48	83.06	72.93
21	1.839E-05	13.71	10.40	96.56	90.23	18.62	13.01	72.37	60.96	19.69	13.52	84.18	74.26
22	1.819E-05	12.62	9.68	96.83	90.53	17.27	12.21	74.37	61.80	19.76	13.40	84.12	74.93
23	1.892E-05	11.43	8.80	97.13	91.23	16.89	11.72	74.93	63.76	18.42	12.44	85.20	76.47
24	1.831E-05	10.40	8.16	97.39	91.30	16.08	11.29	76.13	63.98	18.17	12.29	85.40	76.64
25	1.859E-05	10.38	8.05	97.39	91.74	15.30	10.72	77.29	65.27	17.11	11.58	86.25	77.63
26	1.860E-05	9.16	7.24	97.70	92.04	15.52	10.70	76.97	66.16	16.98	11.38	86.36	78.31
27	1.850E-05	8.73	6.92	97.81	92.27	15.05	10.37	77.67	66.88	16.44	11.01	86.80	78.86
28	1.891E-05	8.05	6.41	97.98	92.68	13.48	9.44	79.99	68.16	15.98	10.60	87.16	79.81
29	1.823E-05	8.03	6.40	97.99	92.67	13.82	9.61	79.49	68.12	15.07	10.20	87.89	79.79
30	1.934E-05	7.47	5.93	98.13	93.27	13.61	9.23	79.80	70.11	15.08	9.89	87.88	81.25

Table B-22 Values of K_{exp} , predicted concentration, and removal efficiency as a function of diameter.
(Negatively charged water spray + Corn starch)

dp (μm)	Avg. initial conc.	Avg. final conc.	K_{exp}	R1			R2			R3		
				Initial conc.	Predicted eff.	Predicted conc.	Initial conc.	Predicted eff.	Predicted conc.	Initial conc.	Predicted eff.	Predicted conc.
0.542	18.43	15.25	2.09E-05	23.40	20.91	18.51	58.60	39.84	35.26	46.10	34.25	30.31
0.583	25.33	24.10	3.72E-06	35.30	6.62	32.96	83.90	14.41	71.81	61.00	10.91	54.35
0.626	33.88	33.25	1.03E-06	59.10	3.18	57.22	121.00	6.29	113.39	87.20	4.62	83.18
0.673	43.58	43.75	-1.70E-07	74.70	-0.69	75.22	148.00	-1.38	150.04	99.60	-0.92	100.52
0.723	52.63	52.28	2.36E-07	94.60	1.19	93.47	182.00	2.26	177.88	122.00	1.53	120.14
0.777	55.15	54.90	1.53E-07	91.50	0.75	90.81	188.00	1.53	185.13	140.00	1.14	138.40
0.835	56.40	54.03	1.44E-06	88.80	6.47	83.05	192.00	13.02	167.01	151.00	10.53	135.10
0.898	52.35	52.40	-3.38E-08	83.20	-0.15	83.33	181.00	-0.33	181.60	154.00	-0.28	154.43
0.965	49.35	46.55	2.26E-06	77.00	8.58	70.39	159.00	16.23	133.19	158.00	16.15	132.49
1.037	45.83	42.48	3.19E-06	65.30	10.10	58.70	146.00	20.08	116.68	143.00	19.75	114.76
1.114	40.48	34.45	8.00E-06	58.30	20.12	46.57	128.00	35.61	82.42	142.00	38.03	88.00
1.197	36.73	32.05	7.36E-06	51.30	16.93	42.62	110.00	30.41	76.55	125.00	33.18	83.53
1.286	32.78	26.50	1.34E-05	47.00	25.35	35.09	92.70	40.11	55.52	130.00	48.43	67.04
1.382	29.43	22.33	2.00E-05	36.60	28.35	26.23	81.20	46.74	43.25	119.00	56.26	52.05
1.486	25.88	18.88	2.65E-05	32.60	31.85	22.22	63.10	47.49	33.13	109.00	60.97	42.54
1.596	23.73	15.80	3.92E-05	31.50	39.97	18.91	58.20	55.17	26.09	98.10	67.47	31.91
1.715	19.55	14.13	3.64E-05	25.00	32.94	16.77	50.70	49.90	25.40	86.80	63.03	32.09
1.843	18.48	10.68	7.32E-05	21.60	46.07	11.65	42.90	62.92	15.91	81.20	76.26	19.28
1.981	15.28	8.10	1.07E-04	20.30	54.07	9.32	36.20	67.73	11.68	71.00	80.46	13.87
2.129	15.15	5.95	1.89E-04	17.50	64.11	6.28	27.50	73.73	7.22	71.30	87.92	8.61
2.288	12.80	5.48	1.94E-04	14.60	60.41	5.78	24.20	71.67	6.86	61.60	86.56	8.28
2.458	11.05	4.18	2.76E-04	15.90	70.32	4.72	23.60	77.86	5.22	54.70	89.07	5.98
2.642	10.68	3.93	2.98E-04	14.20	69.58	4.32	21.40	77.52	4.81	57.30	90.23	5.60
2.839	9.50	3.03	4.17E-04	11.90	72.84	3.23	18.60	80.74	3.58	46.80	91.34	4.05
3.051	8.53	2.45	5.39E-04	10.10	74.60	2.56	14.70	81.05	2.79	41.90	92.42	3.18
3.278	7.25	1.65	8.67E-04	8.20	79.33	1.69	14.80	87.39	1.87	37.10	94.56	2.02
3.523	7.40	1.53	9.64E-04	10.70	84.78	1.63	11.90	86.10	1.65	27.00	93.36	1.79
3.786	6.95	1.38	1.08E-03	9.40	84.58	1.45	9.90	85.24	1.46	25.00	93.58	1.60
4.068	7.35	1.14	1.38E-03	8.69	86.61	1.16	8.99	87.00	1.17	25.50	94.99	1.28
4.371	7.29	1.12	1.40E-03	10.00	88.29	1.17	9.39	87.62	1.16	21.90	94.29	1.25
4.698	7.71	1.11	1.43E-03	9.07	87.53	1.13	9.07	87.53	1.13	24.40	94.97	1.23
5.048	9.63	1.18	1.37E-03	10.20	88.31	1.19	10.00	88.10	1.19	20.80	93.90	1.27
5.425	10.82	1.59	9.97E-04	12.70	87.24	1.62	10.10	84.47	1.57	21.10	91.91	1.71
5.829	13.36	1.28	1.31E-03	14.20	90.94	1.29	11.80	89.30	1.26	21.30	93.77	1.33
6.264	12.88	1.38	1.20E-03	14.50	90.38	1.39	12.40	88.94	1.37	25.20	94.23	1.45
6.732	14.40	1.32	1.27E-03	13.30	90.14	1.31	13.50	90.27	1.31	22.80	94.00	1.37
7.234	14.78	1.28	1.32E-03	16.60	92.22	1.29	16.20	92.04	1.29	24.30	94.55	1.32
7.774	16.35	1.21	1.42E-03	18.50	93.43	1.22	12.20	90.36	1.18	21.00	94.17	1.22
8.354	15.78	0.99	1.76E-03	18.40	94.58	1.00	12.50	92.23	0.97	23.00	95.62	1.01
8.977	17.08	0.82	2.15E-03	18.90	95.63	0.83	14.10	94.23	0.81	21.00	96.05	0.83
9.647	17.43	0.54	3.36E-03	19.10	97.19	0.54	11.40	95.38	0.53	24.10	97.76	0.54
10.37	16.75	0.78	2.26E-03	22.40	96.47	0.79	14.20	94.54	0.78	21.00	96.24	0.79
11.14	17.08	0.56	3.22E-03	26.70	97.89	0.56	14.10	96.09	0.55	24.30	97.69	0.56
11.97	19.60	0.38	4.84E-03	27.00	98.60	0.38	11.00	96.64	0.37	20.30	98.15	0.38
12.86	20.18	0.49	3.68E-03	26.40	98.13	0.49	12.10	96.01	0.48	21.40	97.70	0.49
13.82	20.38	0.28	6.45E-03	32.50	99.12	0.28	12.10	97.68	0.28	25.10	98.87	0.28
14.86	17.20	0.20	9.15E-03	32.20	99.38	0.20	12.40	98.39	0.20	20.20	99.01	0.20
15.96	17.95	0.08	2.30E-02	37.40	99.79	0.08	14.70	99.46	0.08	16.80	99.52	0.08
17.15	15.48	0.06	3.07E-02	30.20	99.80	0.06	7.21	99.17	0.06	14.70	99.59	0.06
18.43	11.48	0.05	3.69E-02	25.70	99.80	0.05	9.00	99.45	0.05	8.75	99.43	0.05
19.81	8.04	0.04	4.61E-02	20.30	99.80	0.04	5.14	99.22	0.04	7.84	99.49	0.04

Initial at t=0, final at t=10

Table B-23 Values of K_{exp} , predicted concentration, and removal efficiency as a function of diameter.
(No water spray + Corn starch)

dp (μm)	Avg. initial conc.	Avg. final conc.	K_{exp}	R1			R2			R3		
				Initial conc.	Predicted eff.	Predicted conc.	Initial conc.	Predicted eff.	Predicted conc.	Initial conc.	Initial conc.	Predicted eff.
0.542	26.47	19.47	2.52E-05	54.10	42.36	31.18	42.00	36.33	26.74	15.00	16.93	12.46
0.583	39.20	29.13	1.63E-05	80.50	41.51	47.09	52.40	31.60	35.84	24.20	17.58	19.95
0.626	53.57	39.03	1.29E-05	111.00	43.55	62.66	67.40	31.90	45.90	31.00	17.73	25.50
0.673	72.67	51.77	1.03E-05	145.00	44.62	80.30	81.10	31.06	55.91	33.60	15.73	28.31
0.723	87.10	64.90	7.27E-06	172.00	40.32	102.66	83.10	24.61	62.65	40.80	13.81	35.17
0.777	97.00	69.93	7.39E-06	183.00	42.20	105.77	80.70	24.36	61.04	40.10	13.79	34.57
0.835	103.77	73.67	7.29E-06	196.00	43.56	110.62	77.70	23.43	59.50	44.00	14.77	37.50
0.898	101.90	72.73	7.29E-06	189.00	42.65	108.39	74.30	22.62	57.49	38.50	13.16	33.43
0.965	97.90	68.40	8.16E-06	189.00	45.43	103.13	64.00	21.99	49.92	39.10	14.69	33.35
1.037	87.93	64.17	7.80E-06	171.00	41.87	99.40	60.80	20.39	48.40	35.40	12.98	30.81
1.114	81.90	60.67	7.91E-06	161.00	40.76	95.38	54.40	18.86	44.14	30.00	11.36	26.59
1.197	71.40	55.00	7.73E-06	153.00	38.99	93.35	50.00	17.27	41.36	26.90	10.10	24.18
1.286	67.10	47.50	1.14E-05	134.00	45.18	73.46	45.60	21.90	35.61	23.20	12.49	20.30
1.382	55.67	43.10	9.70E-06	123.00	39.18	74.81	39.60	17.18	32.80	21.50	10.12	19.32
1.486	48.20	37.13	1.15E-05	116.00	41.77	67.55	36.30	18.33	29.65	19.50	10.76	17.40
1.596	43.30	31.67	1.57E-05	105.00	47.11	55.53	31.20	20.93	24.67	18.50	13.57	15.99
1.715	37.70	29.47	1.37E-05	89.60	39.91	53.84	30.40	18.39	24.81	17.80	11.65	15.73
1.843	34.80	27.23	1.48E-05	85.00	40.43	50.64	28.50	18.54	23.22	14.70	10.50	13.16
1.981	30.20	23.13	1.87E-05	75.60	43.33	42.84	25.80	20.70	20.46	14.50	12.79	12.65
2.129	26.17	20.90	1.78E-05	64.20	38.21	39.67	23.60	18.52	19.23	10.80	9.42	9.78
2.288	23.40	17.53	2.65E-05	59.60	46.01	32.18	21.40	23.43	16.39	9.90	12.40	8.67
2.458	21.50	14.93	3.79E-05	54.50	52.71	25.77	21.60	30.64	14.98	9.10	15.69	7.67
2.642	18.50	14.03	3.19E-05	47.70	45.08	26.20	19.80	25.41	14.77	9.50	14.05	8.17
2.839	17.83	12.67	4.24E-05	43.50	49.87	21.80	15.50	26.17	11.44	7.40	14.48	6.33
3.051	15.57	11.67	3.98E-05	36.40	43.87	20.43	16.00	25.57	11.91	7.90	14.50	6.75
3.278	12.63	9.77	4.30E-05	30.20	41.23	17.75	14.10	24.68	10.62	8.20	16.00	6.89
3.523	11.33	9.60	2.95E-05	23.90	27.58	17.31	11.60	15.60	9.79	6.80	9.77	6.14
3.786	10.57	8.20	5.06E-05	20.80	36.23	13.26	11.40	23.74	8.69	4.70	11.38	4.17
4.068	13.18	7.39	1.10E-04	17.90	51.52	8.68	12.20	42.00	7.08	5.56	24.82	4.18
4.371	10.75	7.26	8.27E-05	14.30	38.99	8.72	12.00	34.90	7.81	5.41	19.47	4.36
4.698	11.59	6.84	1.11E-04	15.50	48.17	8.03	13.70	45.10	7.52	7.11	29.89	4.98
5.048	11.78	8.30	6.60E-05	14.60	34.21	9.61	16.00	36.30	10.19	7.26	20.55	5.77
5.425	12.28	8.39	6.99E-05	14.60	35.52	9.41	15.30	36.60	9.70	6.67	20.11	5.33
5.829	14.80	8.40	9.53E-05	15.20	43.90	8.53	16.30	45.63	8.86	10.20	34.43	6.69
6.264	14.40	9.59	6.44E-05	14.40	33.38	9.59	17.20	37.44	10.76	11.40	28.40	8.16
6.732	15.10	9.53	7.17E-05	15.40	37.37	9.65	17.40	40.27	10.39	13.50	34.34	8.86
7.234	15.77	8.66	9.65E-05	15.60	44.83	8.61	15.20	44.19	8.48	13.20	40.75	7.82
7.774	16.97	8.14	1.18E-04	13.10	45.55	7.13	14.80	48.59	7.61	11.30	41.92	6.56
8.354	17.77	6.14	1.97E-04	13.70	59.33	5.57	13.60	59.16	5.55	13.00	58.06	5.45
8.977	16.47	6.57	1.69E-04	15.30	58.31	6.38	12.10	52.52	5.75	12.70	53.72	5.88
9.647	17.67	5.48	2.33E-04	14.80	65.09	5.17	12.90	61.91	4.91	15.00	65.40	5.19
10.37	16.73	4.38	3.12E-04	14.70	71.27	4.22	11.60	66.18	3.92	11.90	66.75	3.96
11.14	16.33	4.45	3.03E-04	15.00	71.06	4.34	12.90	67.86	4.15	12.50	67.17	4.10
11.97	16.67	4.00	3.51E-04	14.90	73.88	3.89	10.80	67.21	3.54	10.80	67.21	3.54
12.86	18.63	3.87	3.80E-04	13.40	73.31	3.58	11.70	70.57	3.44	12.30	71.60	3.49
13.82	17.30	2.89	5.33E-04	11.30	76.48	2.66	10.50	75.14	2.61	11.10	76.16	2.65
14.86	17.67	2.07	7.91E-04	10.10	81.19	1.90	10.90	82.32	1.93	13.40	85.13	1.99
15.96	16.27	1.49	1.13E-03	8.42	83.71	1.37	9.17	84.84	1.39	10.20	86.16	1.41
17.15	13.64	1.24	1.36E-03	5.79	80.91	1.11	6.92	83.51	1.14	8.37	85.97	1.17
18.43	12.32	0.50	3.55E-03	5.00	90.56	0.47	7.22	93.27	0.49	7.25	93.29	0.49
19.81	8.18	0.27	6.62E-03	3.48	92.56	0.26	5.29	94.98	0.27	3.24	92.06	0.26
<u>Initial at t=0,</u>				<u>final at t=10</u>								

Table B-24 Values of K_{exp} , predicted concentration, and removal efficiency as a function of diameter.
(Negatively charged water spray + $NaHCO_3$)

dp (μm)	Avg. initial conc.	Avg. final conc.	K_{exp}	R1			R2			R3		
				Initial conc.	Predicted eff.	Predicted conc.	Initial conc.	Predicted eff.	Predicted conc.	Initial conc.	Initial conc.	Predicted eff.
0.542	284.00	96.18	1.27E-05	258.00	63.95	93.01	155.00	51.59	75.03	212.00	59.31	86.26
0.583	376.40	129.80	9.35E-06	370.00	65.13	129.03	214.00	51.93	102.88	273.00	57.95	114.81
0.626	505.60	170.00	7.23E-06	497.00	65.99	169.02	295.00	53.53	137.09	368.00	58.96	151.01
0.673	641.00	214.20	5.76E-06	645.00	66.72	214.64	371.00	53.56	172.30	461.00	58.90	189.48
0.723	768.00	257.00	4.79E-06	810.00	67.71	261.54	469.00	54.84	211.81	549.00	58.70	226.73
0.777	846.20	273.80	4.58E-06	891.00	68.76	278.33	524.00	56.42	228.37	597.00	59.59	241.22
0.835	870.00	274.80	4.61E-06	917.00	69.54	279.32	544.00	57.53	231.06	608.00	60.22	241.88
0.898	830.00	259.80	4.90E-06	902.00	70.46	266.46	536.00	58.63	221.73	588.00	60.86	230.15
0.965	770.60	231.20	5.61E-06	853.00	72.09	238.10	492.00	59.83	197.62	543.00	62.18	205.37
1.037	685.20	207.40	6.23E-06	773.00	72.21	214.78	453.00	60.37	179.54	487.00	62.08	184.65
1.114	593.60	177.00	7.34E-06	678.00	72.89	183.82	395.00	61.03	153.92	420.00	62.48	157.58
1.197	503.20	147.60	8.87E-06	594.00	73.99	154.53	333.00	61.45	128.36	355.00	62.96	131.50
1.286	412.00	121.40	1.08E-05	488.00	73.93	127.24	282.00	62.10	106.88	296.00	63.23	108.83
1.382	340.20	102.42	1.26E-05	399.00	73.14	107.17	223.00	60.35	88.43	244.00	62.48	91.55
1.486	270.60	82.70	1.55E-05	314.00	72.50	86.35	190.00	61.47	73.21	202.00	62.91	74.92
1.596	220.60	67.16	1.92E-05	262.00	73.07	70.55	136.00	58.48	56.47	158.00	62.07	59.93
1.715	183.40	52.06	2.55E-05	220.00	75.16	54.64	126.00	63.41	46.10	143.00	66.30	48.19
1.843	148.00	42.22	3.13E-05	166.00	73.75	43.57	103.00	63.55	37.54	110.00	65.06	38.43
1.981	127.60	35.58	3.75E-05	148.00	75.00	37.00	83.80	62.94	31.05	97.00	66.29	32.70
2.129	107.44	27.92	4.91E-05	120.00	76.08	28.70	70.90	65.27	24.62	82.10	68.52	25.85
2.288	93.44	23.72	5.83E-05	106.00	76.93	24.46	61.90	66.07	21.00	66.80	67.76	21.54
2.458	79.36	18.80	7.52E-05	86.30	77.79	19.17	55.40	69.22	17.05	56.00	69.45	17.11
2.642	70.68	17.14	8.18E-05	73.10	76.36	17.28	44.20	66.14	14.97	55.30	70.96	16.06
2.839	60.18	12.98	1.12E-04	69.00	80.66	13.35	39.60	70.53	11.67	43.80	72.58	12.01
3.051	54.22	9.70	1.57E-04	60.70	83.71	9.89	34.90	74.71	8.83	40.00	77.20	9.12
3.278	45.58	8.00	1.91E-04	50.80	83.96	8.15	30.00	75.56	7.33	33.80	77.70	7.54
3.523	43.56	6.04	2.64E-04	46.10	86.80	6.09	27.90	79.91	5.60	30.40	81.26	5.70
3.786	36.82	5.32	2.98E-04	43.10	87.39	5.43	25.40	80.33	5.00	26.80	81.17	5.05
4.068	33.10	4.53	3.53E-04	32.60	86.15	4.52	21.80	80.61	4.23	24.30	82.25	4.31
4.371	29.54	3.55	4.59E-04	32.40	88.93	3.59	16.50	80.35	3.24	25.70	86.43	3.49
4.698	25.40	2.76	5.97E-04	28.50	90.19	2.80	15.60	83.42	2.59	20.50	86.86	2.69
5.048	23.74	2.13	7.92E-04	24.10	91.16	2.13	13.10	84.86	1.98	17.30	88.10	2.06
5.425	20.30	1.55	1.10E-03	20.50	92.44	1.55	12.20	87.92	1.47	17.20	91.12	1.53
5.829	17.56	1.27	1.36E-03	18.00	92.96	1.27	11.10	89.06	1.21	11.90	89.72	1.22
6.264	15.74	1.01	1.72E-03	14.90	93.25	1.01	7.36	87.22	0.94	12.20	91.88	0.99
6.732	13.42	0.71	2.48E-03	14.00	94.94	0.71	6.12	89.14	0.66	9.53	92.74	0.69
7.234	10.69	0.44	4.04E-03	11.20	96.07	0.44	5.37	92.14	0.42	6.83	93.72	0.43
7.774	10.89	0.46	3.89E-03	12.40	96.31	0.46	5.06	91.41	0.43	8.10	94.46	0.45
8.354	9.10	0.13	1.38E-02	12.20	98.92	0.13	3.82	96.62	0.13	6.97	98.12	0.13
8.977	7.31	0.22	8.19E-03	9.59	97.70	0.22	3.42	93.80	0.21	4.93	95.62	0.22
9.647	6.61	0.29	6.20E-03	6.00	95.26	0.28	3.14	91.31	0.27	4.86	94.21	0.28
10.37	5.79	0.06	3.06E-02	6.12	99.02	0.06	2.24	97.37	0.06	4.48	98.67	0.06
11.14	5.14	0.06	2.88E-02	6.03	98.94	0.06	1.27	95.17	0.06	3.02	97.91	0.06
11.97	4.63	0.10	1.81E-02	5.00	98.00	0.10	2.17	95.50	0.10	3.67	97.29	0.10
12.86	4.00	0.07	2.54E-02	6.25	98.85	0.07	2.14	96.71	0.07	2.14	96.71	0.07
13.82	3.55	0.15	1.17E-02	2.83	94.72	0.15	1.32	89.33	0.14	2.83	94.72	0.15
14.86	2.84	0.04	4.56E-02	3.60	98.89	0.04	0.60	93.67	0.04	1.60	97.53	0.04
15.96	2.60	0.09	2.10E-02	2.98	97.13	0.09	0.85	90.62	0.08	1.49	94.42	0.08
17.15	1.91	0.05	3.88E-02	2.33	97.99	0.05	0.00			1.40	96.70	0.05
18.43	1.65	0.03	6.06E-02	1.00			0.00			0.75		0.03
19.81	1.35	0.02	9.12E-02	1.35			0.00			0.54		0.02

Initial at t=0, final at t=10

Table B-25 Values of K_{exp} , predicted concentration, and removal efficiency as a function of diameter.
(No water spray + $NaHCO_3$)

dp (μm)	Avg. initial conc.	Avg. final conc.	K_{exp}	R1			R2			R3		
				Initial conc.	Predicted eff.	Predicted conc.	Initial conc.	Predicted eff.	Predicted conc.	Initial conc.	Predicted eff.	Predicted conc.
0.542	325.33	221.67	2.66E-06	322.00	31.64	220.11	262.00	27.36	190.32	586.00	45.72	318.07
0.583	438.67	303.33	1.88E-06	424.00	30.13	296.25	343.00	25.86	254.29	705.00	41.76	410.59
0.626	592.33	413.00	1.36E-06	521.00	27.64	377.01	441.00	24.43	333.26	862.00	38.72	528.22
0.673	774.67	547.67	9.91E-07	631.00	25.24	471.73	544.00	22.54	421.36	1030.0	35.53	664.04
0.723	946.67	668.67	8.13E-07	699.00	23.49	534.82	604.00	20.96	477.37	1140.0	33.36	759.67
0.777	1040.3	739.67	7.24E-07	738.00	22.38	572.82	628.00	19.70	504.26	1210.0	32.10	821.57
0.835	1075.7	769.00	6.87E-07	730.00	21.30	574.52	620.00	18.69	504.12	1230.0	31.32	844.78
0.898	1040.7	745.33	7.05E-07	691.00	20.83	547.06	589.00	18.32	481.10	1120.0	29.90	785.17
0.965	960.67	694.33	7.39E-07	609.00	19.56	489.88	513.00	17.00	425.78	1050.0	29.54	739.83
1.037	852.67	624.33	7.94E-07	553.00	19.17	446.98	457.00	16.39	382.10	941.00	28.76	670.41
1.114	734.33	537.67	9.22E-07	467.00	18.87	378.87	387.00	16.16	324.46	791.00	28.26	567.43
1.197	623.67	453.00	1.12E-06	393.00	19.19	317.60	318.00	16.11	266.76	662.00	28.57	472.89
1.286	516.00	380.67	1.28E-06	326.00	18.34	266.21	265.00	15.44	224.09	549.00	27.44	398.33
1.382	413.00	307.00	1.55E-06	259.00	17.80	212.90	218.00	15.42	184.39	457.00	27.64	330.67
1.486	337.33	246.33	2.03E-06	215.00	19.06	174.03	167.00	15.46	141.18	367.00	28.67	261.79
1.596	276.00	195.67	2.75E-06	175.00	20.66	138.85	134.00	16.62	111.73	295.00	30.50	205.03
1.715	223.33	162.83	3.08E-06	148.00	19.76	118.76	113.00	15.82	95.12	244.00	28.87	173.55
1.843	186.00	135.73	3.69E-06	128.00	20.31	102.00	94.80	15.88	79.75	209.00	29.38	147.59
1.981	156.43	112.40	4.64E-06	107.00	21.13	84.39	79.20	16.55	66.09	167.00	29.49	117.75
2.129	129.20	92.77	5.63E-06	95.70	22.54	74.13	64.00	16.29	53.58	151.00	31.46	103.49
2.288	111.20	78.87	6.83E-06	84.20	23.69	64.25	58.00	17.62	47.78	125.00	31.55	85.57
2.458	94.33	68.13	7.55E-06	69.80	22.15	54.34	49.70	16.85	41.33	107.00	30.37	74.50
2.642	84.17	61.77	7.98E-06	60.40	20.65	47.93	45.00	16.24	37.69	96.60	29.39	68.21
2.839	74.43	53.97	9.44E-06	53.20	21.33	41.85	39.30	16.68	32.74	87.00	30.71	60.28
3.051	63.73	48.57	9.07E-06	46.70	18.62	38.00	31.40	13.33	27.21	79.00	27.91	56.95
3.278	55.57	42.40	1.03E-05	39.50	18.08	32.36	28.50	13.74	24.58	63.40	26.16	46.81
3.523	54.80	39.27	1.34E-05	36.50	20.85	28.89	25.10	15.34	21.25	56.80	29.08	40.28
3.786	45.73	33.50	1.48E-05	32.00	20.35	25.49	20.80	14.24	17.84	50.40	28.70	35.94
4.068	40.87	30.10	1.62E-05	25.60	18.31	20.91	18.00	13.61	15.55	44.00	27.80	31.77
4.371	38.13	27.97	1.77E-05	22.00	17.34	18.19	16.20	13.38	14.03	39.50	27.35	28.69
4.698	33.00	23.03	2.43E-05	20.30	21.02	16.03	14.30	15.79	12.04	39.60	34.18	26.07
5.048	29.37	19.99	2.96E-05	17.70	22.03	13.80	12.00	16.08	10.07	35.20	35.98	22.54
5.425	27.17	17.68	3.66E-05	14.60	22.39	11.33	9.89	16.35	8.27	30.90	37.91	19.18
5.829	21.47	12.86	5.78E-05	12.00	27.24	8.73	9.27	22.43	7.19	25.70	44.50	14.26
6.264	18.92	11.61	6.16E-05	10.50	25.89	7.78	6.40	17.55	5.28	21.70	41.92	12.60
6.732	16.18	9.69	7.67E-05	8.78	26.66	6.44	4.95	17.01	4.11	18.20	42.97	10.38
7.234	13.83	9.33	6.45E-05	6.65	18.81	5.40	4.93	14.66	4.21	14.50	33.56	9.63
7.774	12.98	7.84	9.34E-05	6.13	23.62	4.68	3.01	13.18	2.61	13.90	41.22	8.17
8.354	10.70	4.60	2.29E-04	5.14	38.89	3.14	3.36	29.38	2.37	10.90	57.44	4.64
8.977	8.78	3.51	3.16E-04	5.45	48.20	2.82	2.46	29.58	1.73	11.10	65.46	3.83
9.647	8.18	3.33	3.29E-04	3.21	36.33	2.04	1.44	20.38	1.15	10.30	64.67	3.64
10.37	7.26	3.23	3.18E-04	3.93	40.28	2.35	2.08	26.30	1.53	8.81	60.19	3.51
11.14	6.08	2.28	5.09E-04	3.12	46.19	1.68	1.22	25.13	0.91	7.14	66.27	2.41
11.97	4.67	1.78	6.46E-04	2.24	43.87	1.26	0.68	19.06	0.55	5.83	67.04	1.92
12.86	4.23	0.89	1.63E-03	1.24	52.26	0.59	0.73	39.03	0.44	6.07	84.27	0.95
13.82	3.84	0.63	2.46E-03	1.09	59.17	0.45	0.57	42.98	0.32	6.04	88.92	0.67
14.86	3.13	0.80	1.72E-03	0.48	30.75	0.33	0.20	15.96	0.17	4.60	81.07	0.87
15.96	2.48	0.57	2.53E-03	0.92	55.54	0.41	0.22	22.83	0.17	3.40	82.26	0.60
17.15	1.63	0.31	4.84E-03	0.29	42.93	0.16	0.22	36.07	0.14	3.26	89.49	0.34
18.43	1.58	0.33	4.39E-03							2.00	82.57	0.35
19.81	1.35	0.18	8.92E-03							2.97	93.46	0.19
<u>Initial at t=0,</u>				<u>final at t=10</u>								

Data for Chapter 7

Table B-26 Laboratory evaluation of the electrostatically-assisted particulate wet scrubber.

Powder	Scrubber air velocity (m/s)	Spray type	Removal efficiency (%)	
			Mean	SD
Corn Starch	1.3	Negatively charged spray + GND	67.87	7.64
		Negatively charged spray	78.62	5.22
		Positively charged spray + GND	67.83	11.82
		Positively charged spray	73.04	4.60
		Uncharged spray	57.70	3.67
		No spray	20.89	3.04
	0.7		79.46	3.86
	2.1	Negatively charged spray	42.95	6.33
	2.9		31.98	1.01
	NaHCO ₃	2.9	Negatively charged spray	26.50
		Uncharged spray	23.87	0.14
1.3		Negatively charged spray	55.12	13.06
		Positively charged spray	67.95	4.56

Table B-27 Laboratory evaluation of the negatively-charged electrostatically-assisted particulate wet scrubber (scrubber air velocity of 1.3 m/s).

Replicate	Filter location	Filter weights			Avg. (mg)	Removal efficiency (%)
		Initial (mg)	Final (mg)	Mass collected (mg)		
R1	Inlet	66.78	68.90	2.12	2.10	73.81
		66.28	68.36	2.08		
	Outlet	67.46	68.05	0.59	0.55	
		66.85	67.36	0.51		
R2	Inlet	67.38	69.34	1.96	1.99	83.88
		66.59	68.60	2.01		
	Outlet	67.60	67.95	0.35	0.32	
		67.21	67.50	0.29		
R3	Inlet	70.32	72.28	1.96	1.97	73.79
		72.42	74.39	1.97		
	Outlet	72.52	73.09	0.57	0.52	
		72.60	73.06	0.46		
R4	Inlet	75.08	77.20	2.12	2.09	77.75
		72.66	74.72	2.06		
	Outlet	73.42	73.90	0.48	0.47	
		71.62	72.07	0.45		
R5	Inlet	75.39	77.47	2.08	2.49	86.12
		75.05	77.94	2.89		
	Outlet	71.49	71.87	0.38	0.35	
		72.35	72.66	0.31		
R6	Inlet	72.87	74.58	1.71	1.63	76.38
		74.68	76.23	1.55		
	Outlet	73.79	74.19	0.40	0.39	
		74.08	74.45	0.37		

Table B-28 Laboratory evaluation of the negatively-charged electrostatically-assisted particulate wet scrubber (with grounding, scrubber air velocity of 1.3 m/s).

Replicate	Filter location	Filter weights			Avg. (mg)	Removal efficiency (%)
		Initial (mg)	Final (mg)	Mass collected (mg)		
R1	Inlet	66.37	67.94	1.57	1.49	59.06
		66.85	68.26	1.41		
	Outlet	68.47	69.05	0.58	0.61	
		67.61	68.25	0.64		
R2	Inlet	67.44	68.99	1.55	1.545	72.49
		67.52	69.06	1.54		
	Outlet	68.01	68.48	0.47	0.425	
		66.25	66.63	0.38		
R3	Inlet	72.38	74.41	2.03	2.005	72.07
		72.58	74.56	1.98		
	Outlet	73.46	74.06	0.6	0.56	
		72.25	72.77	0.52		

Table B-29 Laboratory evaluation of the device (no water spray; air velocity of 1.3 m/s).

Replicate	Filter location	Filter weights			Avg. (mg)	Removal efficiency (%)
		Initial (mg)	Final (mg)	Mass collected (mg)		
R1	Inlet	67.45	69.60	2.15	2.18	24.31
		66.43	68.64	2.21		
	Outlet	68.14	69.81	1.67	1.65	
		67.27	68.90	1.63		
R2	Inlet	67.68	69.47	1.79	1.935	19.90
		66.50	68.58	2.08		
	Outlet	67.68	69.29	1.61	1.55	
		68.06	69.55	1.49		
R3	Inlet	67.18	69.23	2.05	2.03	18.47
		67.30	69.31	2.01		
	Outlet	67.61	69.20	1.59	1.655	
		67.59	69.31	1.72		

Table B-30 Laboratory evaluation of the uncharged wet scrubber (scrubber air velocity of 1.3 m/s).

Replicate	Filter location	Filter weights			Avg. (mg)	Removal efficiency (%)
		Initial (mg)	Final (mg)	Mass collected (mg)		
R1	Inlet	67.35	69.06	1.71	1.63	61.04
		66.49	68.04	1.55		
	Outlet	67.12	67.79	0.67	0.64	
		66.99	67.59	0.60		
R2	Inlet	68.55	70.45	1.90	1.79	53.78
		68.21	69.88	1.67		
	Outlet	68.08	68.99	0.91	0.82	
		67.72	68.46	0.74		
R3	Inlet	69.06	71.03	1.97	1.93	58.29
		67.05	68.94	1.89		
	Outlet	68.96	69.88	0.92	0.81	
		68.74	69.43	0.69		

Table B-31 Laboratory evaluation of the positively-charged electrostatically-assisted particulate wet scrubber (scrubber air velocity of 1.3 m/s).

Replicate	Filter location	Filter weights			Avg. (mg)	Removal efficiency (%)
		Initial (mg)	Final (mg)	Mass collected (mg)		
R1	Inlet	67.7	69.51	1.81	1.80	67.78
		67.06	68.85	1.79		
	Outlet	67.86	68.47	0.61	0.58	
		68.8	69.35	0.55		
R2	Inlet	68.62	71.11	2.49	2.41	76.30
		68.1	70.42	2.32		
	Outlet	68.52	69.16	0.64	0.57	
		68.02	68.52	0.5		
R3	Inlet	72.36	74.99	2.63	2.97	75.04
		71.59	74.89	3.3		
	Outlet	65.8	66.59	0.79	0.74	
		65.97	66.66	0.69		

Table B-32 Laboratory evaluation of the negatively-charged electrostatically-assisted particulate wet scrubber (scrubber air velocity of 0.7 m/s).

Replicate	Filter location	Filter weights			Avg. (mg)	Removal efficiency (%)
		Initial (mg)	Final (mg)	Mass collected (mg)		
R1	Inlet	70.17	71.02	0.85	0.84	75.00
		71.54	72.37	0.83		
	Outlet	72.99	73.20	0.21	0.21	
		70.10	70.31	0.21		
R2	Inlet	70.88	71.73	0.85	0.85	81.76
		70.54	71.39	0.85		
	Outlet	71.27	71.41	0.14	0.16	
		71.86	72.03	0.17		
R3	Inlet	71.04	71.93	0.89	0.87	81.61
		71.20	72.05	0.85		
	Outlet	71.90	72.06	0.16	0.16	
		71.74	71.90	0.16		

Table B-33 Laboratory evaluation of the negatively-charged electrostatically-assisted particulate wet scrubber (scrubber air velocity of 2.1 m/s).

Replicate	Filter location	Filter weights			Avg. (mg)	Removal efficiency (%)
		Initial (mg)	Final (mg)	Mass collected (mg)		
R1	Inlet	71.79	72.09	0.3	0.30	50.00
		71.14	71.44	0.3		
	Outlet	71.17	71.31	0.14	0.15	
		70.83	70.99	0.16		
R2	Inlet	69.77	70.26	0.49	0.49	37.76
		70.67	71.16	0.49		
	Outlet	71.61	71.92	0.31	0.31	
		72.36	72.66	0.3		
R3	Inlet	72.33	72.72	0.39	0.37	41.10
		72.42	72.76	0.34		
	Outlet	71.31	71.52	0.21	0.21	
		70.24	70.46	0.22		

Table B-34 Laboratory evaluation of the negatively-charged electrostatically-assisted particulate wet scrubber (scrubber air velocity of 2.9 m/s).

Replicate	Filter location	Filter weights			Avg. (mg)	Removal efficiency (%)
		Initial (mg)	Final (mg)	Mass collected (mg)		
R1	Inlet	71.03	72.60	1.57	1.53	30.82
		70.96	72.44	1.48		
	Outlet	70.17	72.22	2.05	1.06	
		71.13	71.19	0.06		
R2	Inlet	71.89	73.29	1.40	1.43	32.63
		71.77	73.22	1.45		
	Outlet	72.04	73.00	0.96	0.96	
		71.67	72.63	0.96		
R3	Inlet	72.56	73.96	1.40	1.40	32.50
		71.63	73.03	1.40		
	Outlet	70.28	71.19	0.91	0.95	
		70.02	71.00	0.98		

Table B-35 Field evaluation of the electrostatically-assisted particulate wet scrubber .

Treatment	Filter location	Filter weights			Avg. (mg)	Removal efficiency (%)	
		Initial (mg)	Final (mg)	Mass collected (mg)			
Charged spray R1	Inlet	67.95	69.58	2.64	2.87	74.04	
		71.36	71.01	3.1			
	Outlet	71.26	68.86	0.92	0.74		
71.99		68.55	0.57				
Charged spray R2	Inlet	72.45	70.92	1.92	2.02		59.31
		69.57	69.69	2.11			
	Outlet	68.71	69.19	0.92	0.82		
68.61		69.55	0.72				
Charged spray R3	Inlet	68.67	69.93	1.32	1.23	79.59	
		68.08	70.34	1.13			
	Outlet	68.5	68.42	0.38	0.25		
67.16		68.07	0.12				
Charged spray R4	Inlet	68.16	72.85	1.49	1.46		68.38
		68.25	72.68	1.42			
	Outlet	68.46	72.49	0.5	0.46		
69.12		72.87	0.42				
Uncharged spray R1	Inlet	68.41	70.29	0.72	0.64	43.31	
		67.79	69.26	0.55			
	Outlet	68.15	68.99	0.38	0.36		
67.97		69.01	0.34				
Uncharged spray R2	Inlet	68.57	69.8	1.72	1.54		45.13
		73.21	69.86	1.36			
	Outlet	71.16	68.14	0.98	0.85		
71.01		68.87	0.71				
Uncharged spray R3	Inlet	67.41	69.75	1.5	1.5	50.17	
		69.23	69.95	1.49			
	Outlet	68.94	70.04	0.92	0.75		
68.97		68.98	0.57				
No spray R1	Inlet	69.54	69.07	1.28	1.17		28.51
		68.64	69.22	1.07			
	Outlet	68.72	68.66	0.69	0.84		
68.59		69.56	0.99				
No spray R2	Inlet	68.87	73.87	0.66	0.69	20.29	
		67.95	71.88	0.72			
	Outlet	71.36	71.53	0.52	0.55		
71.26		67.99	0.58				
No spray R3	Inlet	71.99	69.51	0.28	0.27		5.56
		72.45	69.2	0.26			
	Outlet	69.57	69.21	0.24	0.25		
68.71		69.81	0.27				
No spray R4	Inlet	68.61	69.19	0.55	0.57	14.04	
		68.67	69.31	0.59			
	Outlet	68.08	69.06	0.47	0.49		
68.5		69.38	0.51				