Removal of airborne swine dust by electrostatic precipitation

S.D. St. GEORGE and J.J.R. FEDDES

Department of Agricultural, Food and Nutritional Science, University of Alberta, Edmonton, AB, Canada T6G 2H2. *Received 15 July 1993; accepted 15 January 1995.*

St. George, S.D. and Feddes, J.J.R. 1995. **Removal of airborne swine dust by electrostatic precipitation**. Can. Agric. Eng. **37**:103-107. An electrostatic precipitator used in conjunction with a recirculation duct was developed to remove airborne swine dust within an environmental chamber. The collection efficiency of the electrostatic precipitator was evaluated by varying applied voltage and airspeed levels. The three applied voltage levels were: -10.3, -11.0 and, -12.1 kVDC. The three airspeed levels were 0.55, 0.76, and 0.95 m•s^{-1}. The overall collection efficiency of the precipitator ranged from 18.5% at an applied voltage of -10.3 kVDC to 96.4% at an applied voltage of -12.1 kVDC. Applied voltage had a significant effect ($P < 0.05$) on collection efficiency. Airspeed did not have a significant effect ($P < 0.05$) on collection efficiency. However, removal efficiency was highest at 0.76 m•s^{-1} for all applied voltages. An applied voltage of -12.1 kVDC produced ozone levels of 0.21 ppm which exceeded the recommended TLV of 0.1 ppm.

Dans une chambre contrôlée un conduit de ventilation et de recirculation équipée d'un précipitateur électro-statique, était utilisé pour enlever la poussière aéroportée d'un parc d'engraissement de porcs. Le taux de récupération de précipitateur était mesuré en utilisant trois niveaux de voltage et de vitesse d'air :-10,3, -11,0 et -12,2 kVDC ainsi que 0,55, 0,76 et 0,95 m•s^{-1}, respectivement. Le taux de récupération des poussières augmentait significativement ($P < 0.05$) de 18,5% à 96.4%, pour un voltage respectif de -10,3 et -12.1 kVDC. Une vitesse d'air de 0,76 m•s^{-1} perforant n'importe le voltage appliqué. Le voltage de -12,1 kVDC produisait un taux d'ozone de 0,21 ppm, ce qui excédait la valeur limite pour les humains de 0,1 ppm.

INTRODUCTION

The trend towards intensified swine production in confinement buildings has led to an increase in airborne contaminants within the animal's and stockperson's environment. The main constituents in airborne dust found in swine barns are feed and fecal particles, but they may also include other organic matter such as dander, urine, mold, pollen, insect parts, and mineral ash (Donham and Leininger 1984). The dust may also carry gram-negative bacteria, endotoxins, adsorbed ammonia (NH_3), and infectious agents (Donham and Leininger 1984).

Research into mechanical dust removal methods for swine barns has included the use of filters, wet scrubbers, ionizers, and electrostatic precipitators. A self cleaning, inexpensive, safe, and highly efficient air cleaning system has not yet been devised for use in swine barns. Electrostatic precipitators are highly efficient at removing small dust particles such as respirable particles found in swine housing (Wark and Warner 1981).

The purpose of this research was to determine the effect of applied voltage and the effect of airspeed on the collection efficiency of an electrostatic precipitator used for removing swine housing dust. An electrostatic precipitator specifically designed and fabricated in conjunction with a recirculation duct in an environmental chamber was used for this purpose. Industrial design equations were used to predict the effects of voltage and airspeed on the effective migration velocity of the dust particles.

BACKGROUND

Electrostatic precipitation

The four steps involved in the mechanism of electrostatic precipitation are: 1) the creation of an electric field and corona current; 2) particle charging; 3) particle collection, and 4) removal of the collected dust (McDonald and Dean 1982). The formation of an electric field is accomplished by applying a large potential difference between a small-radius electrode and a much larger radius electrode, where the two electrodes are separated by a region of space containing an insulating gas (McDonald and Dean 1982). At any applied voltage, an electric field exists in the inter-electrode space (the space between the discharge and the collection electrode).

Corona discharge

At voltages higher than the corona starting voltage, the electric field in the vicinity of the discharge wire is large enough to produce ionization by electron impact. The strong field surrounding the discharge wire distorts the orbits of electrons in atoms of the insulating gas so that only a small amount of energy is required to ionize a gas molecule. As the negative discharge ionizes a neutral air molecule, electrons and negative ions move away from the discharge wire at high accelerations while the positive ions migrate toward the discharge wire. The high acceleration of electrons and negative ions from the discharge wire causes them to collide with neutral air molecules passing through the corona glow region. With each collision an extra electron and negative ion are released forming a stream of electrons referred to as an electron avalanche. Once out of the corona region, electrons do not have sufficient energy to ionize more neutral air molecules.

Particle charging

Once the electrons are outside the corona region they drift toward the collection plate, forming an electric field extending from the discharge wire to the collection plate. The space-charge of the electric field is greatest at the discharge wire and decreases to zero at the collection electrode. As a neutral dust particle enters the electric field in the inter-electrode space, it accepts charge until saturated. The rate at which a dust particle becomes charged depends upon particle size as well as current density in the inter-electrode space. As current density increases and particle size decreases, the charging rate increases.

Particle collection

Once the particle is charged, it migrates to the collection plate. The speed at which particle migration occurs is the migration velocity, D (Wark and Warner 1981). This value depends upon the electrical force on the charged particle as well as the drag force developed as the particle moves, perpendicular to the main air flow, toward the collection electrode. Migration velocity is directly proportional to particle diameter and the square of field strength and inversely proportional to gas viscosity (Lloyd 1988). The electric field within the collected dust layer determines how well the dust layer remains in contact with the collection electrode. The electrical resistivity of dust upon the collection electrode determines how well current will pass through the dust layer, either through surface or volume conduction (St. George and Feddes 1995).

Removal of the collected dust layer

The removal of the collected dust layer, not considered in this research, is usually performed by rapping the collection electrodes with a strong force. Collected dust then would fall into the hopper situated below the wires and plates. Entrainment of dust particles into the airstream can result from rapping and may result in a decrease in collection efficiency (McDonald and Dean 1982).

METHODS AND MATERIALS

The design selected for the prototype was based upon an industrial type precipitator. The electrostatic precipitator prototype was a single-phase wire-plate type using negative potential. The three main components of the prototype were: 1) the particle charging mechanism; 2) the particle collection mechanism, and 3) the precipitator enclosure. A frontal view of the prototype is shown in Fig. 1. The particle charging mechanism consisted of 11 wire grids which each contained four 0.78 mm diameter stainless steel wires. Each wire was approximately 0.4 m in length. Each wire grid was placed between two collection plates made of galvanized steel, 0.4 m high and 0.6 m long. The wires connected to the high voltage power supply were located approximately 12.5 mm from the grounded collection plates. The precipitator enclosure consisted of a plywood box connecting the precipitator to the recirculation fan and duct.

The air cleaning system including the electrostatic precipitator and the recirculation duct was tested within an environmental chamber described by Leonard (1986). A split-plot factorial experimental design was used to analyze the dust concentration data. The two independent factors, applied voltage and airspeed through the precipitator, each had three levels. When combined, they yielded nine test

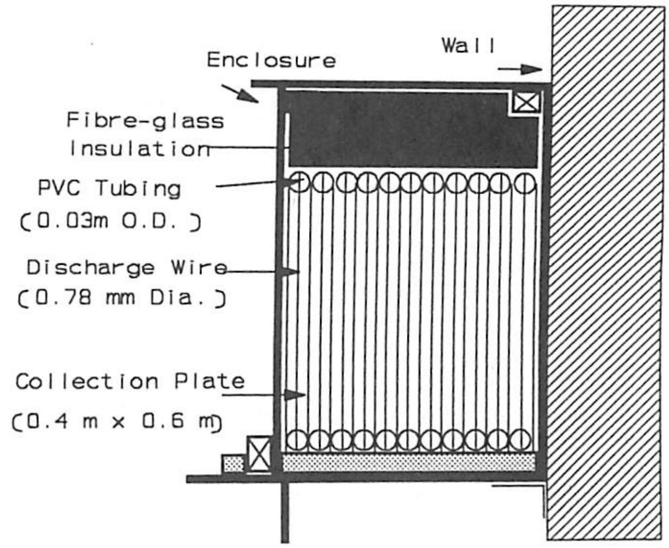

Fig. 1. A frontal view of the electrostatic precipitator prototype.

combinations. Each of these combinations had three replicates which were performed randomly, resulting in a total of twenty-seven runs.

Precipitator voltage levels 1, 2, and 3 were approximately -10.3 kVDC (0.11 mA), -11.0 kVDC (0.28 mA) and -12.1 kVDC (3 mA), respectively. Airspeed levels 1, 2, and 3 through the electrostatic precipitator were 0.55 $m \bullet s^{-1}$, 0.76 $m \bullet s^{-1}$ and 0.95 $m \bullet s^{-1}$, respectively. The airflows through the exhaust fan in the chamber varied from a minimum of 976 $m^3 \bullet h^{-1}$ to a maximum of 4602 $m^3 \bullet h^{-1}$.

The data for this experiment include particle concentrations directly downstream and upstream from the electrostatic precipitator. For each of the ten samples obtained per run a collection efficiency was calculated using Eqs. 1 and 2.

$$\eta_d = 100 \bullet (1 - B \bullet A^{-1}) \tag{1}$$

where:

η_d = collection efficiency for a particle size range d (%),
A = number of particles upstream ($\text{particles} \bullet mL^{-1}$), and
B = number of particles downstream, ($\text{particles} \bullet mL^{-1}$).

$$\eta_o = \Sigma(n_d \bullet \eta_d) \bullet (\Sigma(n_d))^{-1} \tag{2}$$

where:

η_o = overall collection efficiency (%), and
n_d = particle concentration at particle size d ($\text{particles} \bullet mL^{-1}$).

Since the overall collection efficiency does not account for different dust concentrations and airflows between runs, a removal efficiency was calculated using Eq. 3. The removal efficiencies were used to determine the effects of applied voltage and airspeed on the actual collection capacity of the precipitator.

$$\eta_r = \eta_o/100 \bullet Q \bullet N_t \tag{3}$$

where:

η_r = removal efficiency (10^6 particles•s^{-1}),
η_o = overall collection efficiency (%),
Q = airflow (m^3•s^{-1}), and
N_t = total particle concentration, (particles•mL^{-1}).

RESULTS

Particle characteristics

The average total number of particles upstream from the electrostatic precipitator inlet was 40.6 particles•mL^{-1}. The median, modal, and mean particle diameters were 1.7 µm, 1.5 µm, and 1.9 µm, respectively. Through microscopic identification of collected dust particles (starch and fecal origin) were identified in the highest proportions. The fecal particles were the main constituents less than 5 µm.

Overall collection efficiencies

The overall collection efficiencies, η_o, ranged from a minimum of 18.6% at voltage level 1 and airspeed level 3 to a maximum of 96.4% at voltage level 3 and airspeed level 1 as shown in Fig. 2. For the applied voltage level 1, η_o was 37.8%, 27.7%, and 18.6% for airspeed levels 1, 2, and 3, respectively. For applied voltage level 2, η_o was 44.7%, 46.6%, and 47.5% for airspeed levels 1, 2, and 3, respectively. For applied voltage level 3, η_o was 96.4%, 91.1%, and 91.1% for airspeed levels 1, 2, and 3, respectively.

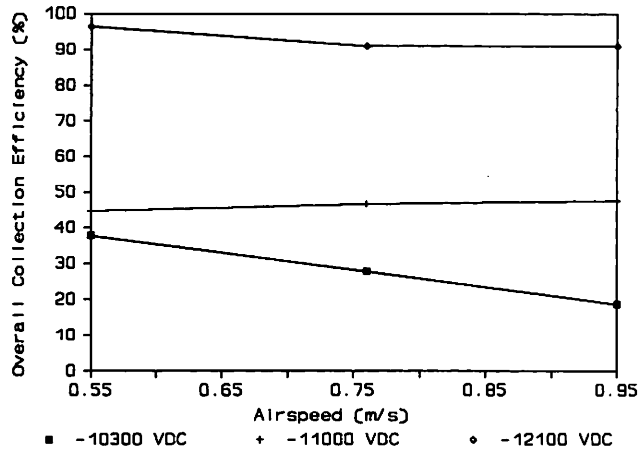

Fig. 2. The effect of applied voltage on overall collection efficiency.

Removal efficiencies

Since airflow through the electrostatic precipitator affected the amount of dust flowing through the system per unit time, a removal efficiency accounted for the dust flows at different air speeds. Removal efficiencies were calculated using Eq. 3. When compared to the variables airspeed and voltage, resulted in different trends from the original collection efficiencies. Figure 3 shows the effect of voltage on the removal efficiencies. The highest removal efficiencies were attained for each of the voltage levels at airspeed level 2.

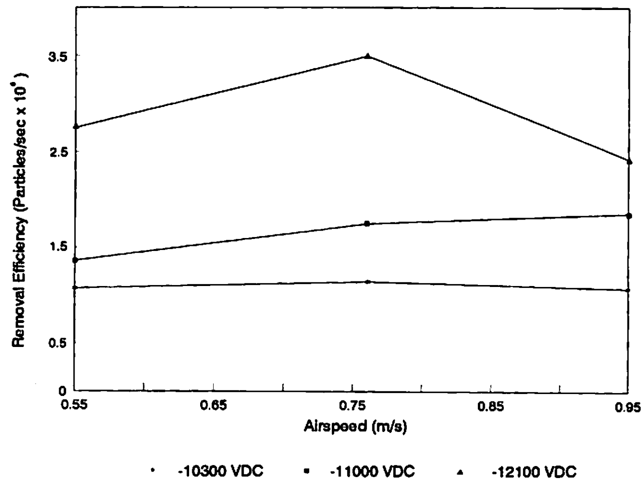

Fig. 3. The effect of applied voltage on removal efficiencies.

Ozone production

The ozone concentrations measured by the gas detector varied from 0 at voltage level 1, to 0.27 ppm at voltage level 3. Airspeed through the electrostatic precipitator did not have an effect on ozone production. Assuming that ozone concentrations measured within the chamber were equal to that removed by the exhaust fan, the total amount of ozone produced for the duration of each run varied from 0 to 333 mL•h^{-1}. Mean ozone production at applied voltage level 3 was 296 mL•h^{-1}. A strong odor of ozone was detected only during runs at applied voltage level 3.

DISCUSSION

Particle characteristics

There were slightly more smaller particles in the dust used in this research than in the dust used in the previous studies (St. George and Feddes 1995). This may be due to the difference in sampling equipment, as well as varying environmental conditions. There was no identification of viable particles such as gram-negative bacteria, infectious agents, or endotoxins in the electron microscopic evaluation of the constituents of dust used in this experiment. Since the dust was collected and stored approximately 30 days before it was used in the experiment, particles could have lost their viability. The identification of particles less than 5 µm as being primarily fecal particles was common to results of this experiment and other studies. Dust concentrations measured in actual swine confinement buildings were much lower than those used in this experiment. The dust concentration of 41 particles•mL^{-1} is representative of periods of high activity in swine confinement buildings and represents the worst case scenario. The dust levels encountered in this research are higher than recommended TLV of 25 particles•mL^{-1} (Donham 1987).

Overall collection efficiency

The electrostatic precipitator used in this research removed up to 94% of dust particles. This efficiency is higher than those yielded by wet scrubbers and filters (Pearson 1986).

Wet scrubbers are more efficient in removing an irritating gas such as NH_3. However, since gases are generally adsorbed onto a particle's surface, removing most of the particles would ultimately remove the gases. Ionization is an efficient method to charge dust particles, however it is most efficient when the ionization occurs within the chamber where the dust is present. Combining an air cleaner with a recirculation fan and/or duct serves two purposes: 1) most of the air within the chamber is drawn through the air cleaner, and 2) the recirculated air contains less dust.

Effect of voltage

The values of voltage and corresponding current levels 1, 2, and 3 were: -10.3 kVDC (0.11 mA), -11.0 kVDC (0.28 mA) and -12.1 kVDC (3.0 mA), respectively. The average collection efficiency for each of the applied voltage levels 1, 2, and 3 were: 28.0%, 46.3%, and 92.9%, respectively. Applied voltage due to the corresponding applied current had a significant effect ($P < 0.05$) on collection efficiency. Since the corresponding current for each voltage level is dependent upon temperature, current is the parameter that controls the strength of the corona discharge. Therefore current rather than voltage level should be the main parameter to be monitored in providing a consistent corona discharge. The collection efficiency for -12.1 kVDC (3.0 mA) at any of the three airspeed levels was higher than at lower applied voltages. The larger the difference in applied current, the larger the difference in effective migration velocity and thus collection efficiency.

Effect of airspeed

The three airspeed levels and corresponding airflows through the precipitator were: 0.55 $m{\bullet}s^{-1}$ (244 $m^3{\bullet}h^{-1}$), 0.76 ms^{-1} (338 $m^3{\bullet}h^{-1}$) and 0.95 $m{\bullet}s^{-1}$ (422 $m^3{\bullet}h^{-1}$), respectively. The average collection efficiency for each of the airspeed levels 1, 2, and 3 were: 59.6%, 55.2%, and 52.4%, respectively. Airspeed did not have a significant effect ($P < 0.05$) upon collection efficiency. With a broader range of airspeed levels, the airspeed was expected to have a significant effect upon collection efficiency. With a lower airspeed, a particle remains within the precipitator longer and the probability of a particle being charged and collected is higher. If the particle passes through the precipitator without being fully charged it may not be collected.

Observation of the collection plates after 1-h indicated that dust collected upon an area directly adjacent to the discharge wires, regardless of applied voltage. Had the drag force of the air affected the migration velocity of the charged particle towards the plate, the dust particles would have collected slightly downstream from the discharge wires. Since this did not occur at any applied voltage or airspeed, the airspeeds appeared to be within a range at which the collection of the particles was not affected.

Operating conditions

The recommended airspeed range for electrostatic precipitators is between 0.3 and 6 $m{\bullet}s^{-1}$ (Wark and Warner 1981). Analyzing the results for overall collection efficiencies at different airspeed levels, airspeed level 1 generally supplied the highest efficiencies. Therefore, based upon these results a low airspeed, such as 0.55 $m{\bullet}s^{-1}$ would be recommended. However, at a lower airspeed the actual airflow, and thus the number of particles passing through the system per unit time, would also be less as compared to those at higher airspeeds. Removal efficiencies based on an equivalence of particles per second were compared, and airspeed level 2 of 0.76 $m{\bullet}s^{-1}$ yielded the highest efficiencies for all voltage levels.

From these results, the airspeed of 0.76 $m{\bullet}s^{-1}$ provides the optimal conditions (of the three airspeed levels tested) within the electrostatic precipitator for particle collection. At this airspeed, the turbulence is such that the occurrence of collisions between particles and ions is higher than at a lower airspeed. However, there is a limit to the amount of turbulence that can be allowed before collection efficiency is decreased. At high speeds, excessive turbulence can cause collected particles to be bumped off the collection plate. As well, the higher airspeed of 0.95 $m{\bullet}s^{-1}$ may have caused the particles to overcome the force due to their migration velocities and leave the precipitator before they were completely charged. To optimize collection efficiency, based on overall and removal collection efficiencies, to optimize collection efficiency, the recommended applied voltage and airspeed levels would be: -12.1 kVDC (3.0 mA) and 0.76 $m{\bullet}s^{-1}$, respectively.

Ozone production

The concentrations of O_3 varied from 0 ppm at an applied voltage of -10.3 kVDC to 0.27 ppm at an applied voltage of -12.2 kVDC. The recommended TLV for O_3, for an 8-h day, 40-h week is 0.1 ppm (ACGIH 1992). At an applied voltage of -12.1 kVDC, the mean O_3 produced was 0.21 ppm. Assuming these concentrations would be constant during an entire day of precipitator operation, the TLV was exceeded at voltage level 3. To reduce the concentrations present in the chamber to recommended levels, the exhaust fan would have to be operated at 0.4 air changes$\bullet min^{-1}$. The mean O_3 produced, at an applied voltage of -12.1 kVDC was 296 $mL{\bullet}h^{-1}$ (97.1 $mL{\bullet}h^{-1}{\bullet}mA^{-1}$).

CONCLUSIONS

From the results, the following conclusions can be drawn:

1. The applied voltage and current levels of -10.3 kVDC (0.11 mA), -11.0 kVDC (0.28 mA) and -12.1 kVDC (3.0 mA) had a significant effect ($P < 0.05$) upon collection efficiency of the prototype electrostatic precipitator.
2. The three levels of airspeeds through the precipitator, of 0.55 $m{\bullet}s^{-1}$ (244 $m^3{\bullet}h^{-1}$), 0.76 $m{\bullet}s^{-1}$ (338 $m^3{\bullet}h^{-1}$) and 0.95 $m{\bullet}s^{-1}$ (422 $m^3{\bullet}h^{-1}$) did not have a significant effect ($P < 0.05$) upon collection efficiency of the prototype electrostatic precipitator.
3. The overall collection efficiency, η_o, increased from 18.6% at an applied voltage of -10.3 kVDC to 96.4% at an applied voltage of -12.1 kVDC.
4. To optimize removal efficiency, the airspeed of 0.76 $m{\bullet}s^{-1}$ should be used at applied voltages between -10.3 and -12.1 kVDC.
5. When applying a voltage and current of -12.1 kVDC (3 mA), the ventilation rates should be sufficient to reduce ozone concentrations to 0.1 ppm.

6. Combining a recirculation duct, self-cleaning mechanism and power supply controller with an electrostatic precipitator is an effective method of dust removal for swine confinement housing.

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