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Using an improved electrostatic precipitator for poultry dust removal

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ABSTRACT

Pubic concerns related to particulate matter emissions from animal housing operations are increasing. The goal of this study was to custom develop a simple and low cost electrostatic precipitator (ESP) for poultry dust control. The performance of the improved electrostatic precipitator (iESP) to remove a test aerosol was evaluated under a series of operating voltages between −60 kV and 60 kV. The mass and size distributions of the particles were measured by a cascade impactor. The overall dust removal efficiency ranged from 37% to 79% with the maximum efficiency obtained at −30 kV. The iESP shows high removal efficiencies for particles less than 2.1 μm.

1. Introduction

Particulate matter (PM, also called dust) and ammonia have been identified by the EPA as the most hazardous air pollutants emitted from concentrated animal feeding operations (CAFOs), such as poultry operations [1]. PM emissions from CAFOs can consist of the feed materials, various body parts, such as dead skins and feathers, dried feces, various microorganisms and endotoxins [2] and tend to be odorous due to microbial activities in the precursor materials of the PM and ammonia emissions. The effects of dust emissions on human and animal health have been widely studied and well recognized [3–5]. The PM concentrations in poultry barns measured can vary widely due to various parameters, such as the types of animals, the growth stage, the configuration of the barns, the different seasons and the measurement methods, etc. [6]. As an example, studies by Ellen et al. [7] have reported that the inhalable PM (PM_{10}) concentrations can vary from 0.02 to 81.33 mg/m^3, and the concentrations of respirable PM (less than 4.0 μm) ranged from 0.01 to 6.5 mg/m^3. More recent studies from a poultry farm in Ohio indicated that the average PM concentrations are generally in the 6–10 mg/m^3 range but can be as high as 10–15 mg/m^3 [6]. As a reference, the Occupational Safety and Health Administration (OSHA) standard for total suspended particles (TSP) and respirable dust at workplaces are 15 mg/m^3 and 5 mg/m^3 respectively [8]. The recommended exposure limit (REL) of the National Institute for Occupational Safety and Health's (NIOSH) is 4 mg/m^3 for grain dust based on time weighted average [9]. The high PM concentrations in some facilities can result in violations and penalties in addition to human or animal health problems.

Therefore, mitigation technologies to control the emissions of ammonia and dust from poultry CAFOs are urgently needed. Currently, there has not been any mature technology developed or in the market for CAFOs dust control. Some PM reduction methods have been under pilot testing, such as impaction curtains, filters, and wet scrubbers.

The impaction curtains placed in front of the exhaust fans can result in considerable pressure drop, which in turn requires a more powerful fan and more energy consumption. A study of impaction curtains reported that the collection efficiency of dust was less than 40% and the cleaning and the replacement process is also complex [10].

Mechanical filter technologies usually need high maintenance in dusty spaces, such as livestock and poultry buildings. They can also cause significant pressure drop, which results in operational difficulties for the existing ventilation systems. These technologies have had some level of success. However, there remains considerable developmental work to be done to achieve high PM removal efficiency and more practical for widespread commercial use.

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Electrostatic precipitators (ESPs) have been used for over 90 years in the control of industrial particulates. The ESP generally consists of charging electrodes (wires) and collection electrodes (plates) with a high voltage applied across them. High voltage is usually applied between the wire and plate, and the formed corona can generate ions that are then attached on the particles in the gas stream. The charged particles will move toward the collection electrode, which is usually grounded for safety reasons. ESPs inherently have low pressure drop since the collection force only acts on the particles instead of the whole flow stream, which will result in lower energy usage comparing with other dust removal methods, such as the baghouse or scrubber, etc. The charging electrodes have very low cross sectional areas to the gas flow, which will not cause much pressure drop either. Thus the ESP will not affect the performance of the ventilation fans in poultry farms unlike other control technologies [11].

An electrostatic space charge system (ESCS) has been designed using the ESP working principles and tested in several poultry houses [12]. The unit distributed negatively ionized air throughout the poultry house by exhaust fans to charge the particles. The negatively charged dust then moved downward to the grounded surfaces and was captured. The average dust removal efficiencies obtained ranged from 37% to 61% [12–14]. However, this inside charging unit used all the grounded surfaces as collection electrodes, including the workers, the chickens, and the machinery, which can be difficult in dust clean up.

The purpose of this study is to custom develop a simple, low cost and yet effective particulate control technology for the removal of poultry dusts using the principles of an ESP. These units will be installed in the ducts of each of the ventilation fans, and therefore needs to be portable, compact, low maintenance needed and low cost. The technical effectiveness in the removal of a test aerosol which has size properties similar to those of poultry dusts was also evaluated.

2. Materials and methods

The experimental system was composed of three main parts: a particle dispersion system, an improved electrostatic precipitator (iESP) system and a cascade impactor to measure concentration of particles in the exhaust.

2.1. iESP design

The iESP (Fig. 1) was fitted in a 101.6 cm × 60.96 cm × 60.96 cm wooden box for portability and affordability. There are 10 parallel charging wires (OD 5 mm, length 60.96 cm) and 44 parallel stainless steel collecting plates (60.96 cm × 2.54 cm × 0.2 cm) inside. The charging electrodes were vertically placed at 5.08 cm apart and were installed 10.16 cm behind the fan. The collecting plates, 1.27 cm apart, were welded to a metal frame so that the distance between the plates and the charging electrodes could be adjusted. Prior to the efficiency tests, collection frame was placed at various locations to find the position with the highest PM removal efficiency, and the collection frame was fixed at this optimum location throughout the study, which is 10.16 cm before the outlet of the iESP box. A high voltage generator (WR100R2.5-11, Glassman Inc.) was used to produce the charging voltages ranged from −60 kV to 60 kV. All metal parts of the iESP system were grounded. A 60.96 cm (24 inch) exhaust fan (Grainger Inc.) was installed in front of the iESP box to disperse the dust into the iESP, which could represent the exhaust fan in the actual poultry farms (usually 48 inches). The flow rate of air was approximately 400 m^3/h, and the average velocity of air flow was 1.7 m/s. Ducts connecting to the iESP unit were well sealed to prevent air leakage. The dusts were collected in a hopper underneath the iESP box. The drawer-like hopper can be pulled out for cleaning. In the experiments, the collecting plates were manually cleaned after each run and the hopper was cleaned daily after four to six runs. A plate rapping system is expected to be installed in future to help clean the collecting plates. The design improvements of this iESP comparing with traditional industrial ESPs included higher turbulence flow, shorter residence time and lower corona power ratio (power consumption) as indicated in Table 1.

2.2. Particle dispersion system

Known quantities of the test aerosol were placed on a turntable particle feeder (Fig. 2 (a)) to be dispersed. The speed of rotation was adjustable and was set to 1/6 revolution per minute. This particle dispersion system has been widely used [15] and is briefly described here. With rotation, the particles were wiped across the groove on the turntable by a rubber wiper, and the groove was filled with particles evenly. Particles from the groove were taken into the gas stream with a "T"-type dust injection unit. The details of this unit are shown in Fig. 2 (b). The air flow, which was generated by an air compressor, was maintained at 25 psi and 60 L per minute by a gas pressure regulator and a flow meter.

2.3. Particle collection device

An 8-stage non-viable ambient cascade impactor (Tisch Environmental Inc., Model 20-800) was utilized to measure the mass of

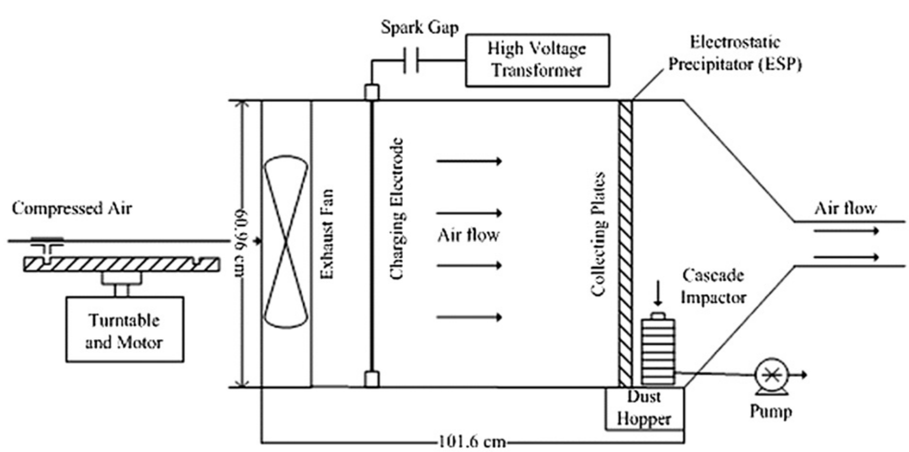

Fig. 1. Schematic drawing of the experimental setup.

Table 1
The comparison of the iESP with industrial ESPs.

Parameters	iESP	Industrial ESPs
Gas velocity (m/s)	1.7	1.5–2.5
Reynolds number (*Re*)	45,000–68,000	5000–25,000
Resident times (s)	0.0015	1–20
Collecting area (m^2)	1.332	460–7000 (per section)
Specific Collection Area ($m^2/(m^3/min)$)	0.200	0.25–2.1
Corona power ratio ($W/(m^3/min)$)	0.01–0.27	1.75–17.5
Corona current ratio ($\mu A/m^2$)	28–140	50–750

Table 2
Size and mass distributions of the test aerosol.

Size range (μm)	Mass percentage
>9	45.74 ± 0.09%
5.8–9	9.98 ± 0.02%
4.7–5.8	11.68 ± 0.03%
3.3–4.7	4.71 ± 0.02%
2.1–3.3	5.46 ± 0.01%
1.1–2.1	3.17 ± 0.01%
0.7–1.1	5.34 ± 0.01%
0.4–0.7	7.75 ± 0.04%
Backup filter	6.17 ± 0.02%

the particles for different size ranges. Cascade impactors have been used to measure the PM sizes in broiler houses [16] and can provide size specific removal efficiencies (grade efficiency) to better evaluate the performance of the iESP. The flow rate of the cascade impactor was 28.3 L per minute. Glass fiber filters (Tisch Environmental Inc., 0.2 μm pore size) were used to collect particles. The filters were dried in a desiccator for more than 24 h and weighed before placed onto the stages of the cascade impactor for sampling. After each measurement, the filters were covered by aluminum foils and put into petri dishes on site and dried for 24 h before weighed again. The mass differences between the weighing after and before measurement were the weights of the particles collected in the specific size range. The dust feeding concentration ranged from 6.7 to 24.5 mg/m^3, which is similar to the concentration ranges observed in the poultry farms. The sampling time was approximately 2 h for each experiment. The size and mass distribution of the test aerosol is shown in Table 2.

2.4. Experimental design

The chicken dust was not used due to difficulty in dispersion (contains moisture) and the odor. Several dusts have been tested, and corn starch was founded as the closest in size distribution (Table 2) with the poultry dusts. The mass median diameter of this dust is 5.96 μm and approximately 46% of the mass is greater than 9 μm and 22% is less than 2.1 μm, which matches the reported size distributions of the poultry dust that 37.9–51.8% of the mass was greater than 10 μm [17]. An ultimate analysis from OKI analytical lab shows the chicken dust contains about 30% calcium, which has lower electrical resistance compared to corn starch. The usage of corn starch is a proof of concept, and testing with chicken dust should be performed before field installation.

The cascade impactor was placed after the collecting plates of iESP as shown in Fig. 1. The original size distribution was measured when the iESP was turned off. Then new filters were conditioned and weighed before putting into the cascade impactor. Samples were collected with the iESP turned on. The removal efficiency of a certain stage (grade efficiency) was calculated by the mass difference of at each stage when iESP turned on and when it was off.

The efficiency has been measured with both positive and negative corona. Negative corona has been used more in the electrostatic charging systems [13,14] in various broiler houses. Positive corona was generally less efficient as negative corona at the same voltage, but it is associated with less ozone generation, and therefore tend to be more suitable with people and animals around [11,18]. Voltages ranging from −60 kV to 60 kV, with 10 kV increments were utilized in this study. Each operating condition was repeated 2–3 times to ensure accuracy, and the relative standard deviations for a set of duplicate samples were less than 12%.

3. Results and discussion

3.1. Overall collection efficiency

The overall collection efficiency was obtained from the grade efficiency at each impact stage. The following eq. (1) is used to calculate the grade efficiency.

$$\eta_i = \frac{m_{on}}{C_{on}} \Big/ \frac{m_{off}}{C_{off}} \times 100\% \quad (1)$$

where, η_i is the grade efficiency (%) of the ith stage, $i = 1, 2, \ldots 8$; m_{on} and C_{on} are mass (mg) of particles collected on the cascade impactor and the feeding concentration (mg/m^3) of particles with iESP turned on; m_{off} and C_{off} are mass (mg) of particles collected on the cascade impactor and the feeding concentration (mg/m^3) of particles with iESP turned off.

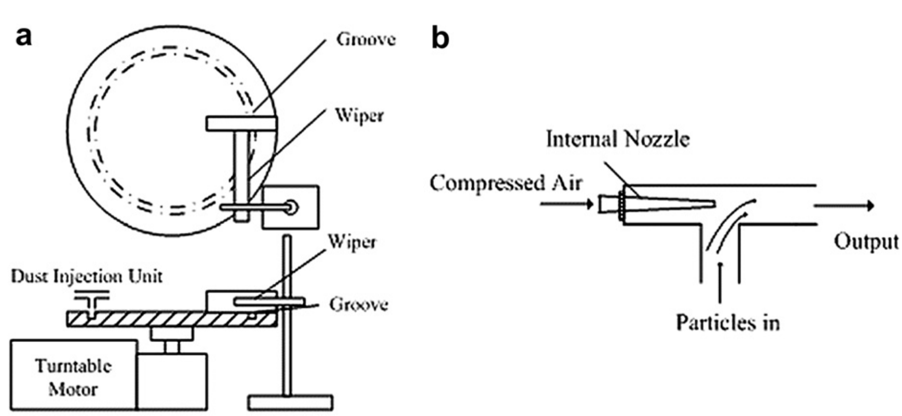

Fig. 2. (a) Schematic drawing of the turntable dust feeder. (b) Details of the dust injection unit.

The overall dust removal efficiency is a weighted average based on the grade efficiencies and masses, shown in eq. (2):

$$\eta_T = \sum_{i=1}^{n} (\eta_i \times m_i) \quad (2)$$

where, η_T is the overall dust removal efficiency (%); m_i is the mass percentage of particles in the ith stage, $i = 1, 2, \ldots 8$.

Fig. 3 shows the overall efficiency at various voltages. Average values are used and the error bars represent the actual differences in the calculation. Under positive voltages, the overall efficiency ranged from 48%–62% and the range was 37%–79% for negative voltages. These values are in agreement with those reported by the ESCS system [13,14]. The efficiencies vary with the types of charging, i.e. positive and negative, and has a larger fluctuation under negative voltages. The trends of overall efficiency under various charging voltages are similar for both positive and negative voltages. The overall efficiency increased from 10 kV to 30 kV, and then decreased. The reason may be related to the corona wind generated at higher voltages, which can result in the re-entrainment of the collected particles back to the gas stream [19,20]. Although the turbulence generated by the corona wind may be less compared to the bulk turbulence, it is more influential near the collection surface. The highest efficiencies occurred at −30 kV: 79% PM removal has been achieved, which is much greater than the highest efficiency impaction curtains tested in some poultry farms (~30%) [10].

3.2. Collection efficiency based on particle size

The particles collected on the eight stages of the cascade impactor were roughly classified into two categories: coarse particles (larger than 2.1 μm, the closest to $PM_{2.5}$) and fine particles (less than 2.1 μm) to further evaluate the effectiveness of the iESP. Approximately 22% (by mass) of the test aerosol resides in the fine region and 78% in coarse region. Fig. 4 shows the efficiencies for fine and coarse particles at various voltages. Under positive voltages, the average removal efficiencies for the fine particles (48–95%) are higher than those for coarse particles (42–57%) under all voltages. The single tailed independent samples t-test was used to statistically evaluate the removal efficiencies of fine and coarse particles. This type of analysis has been widely used for result validation in environmental studies [21]. The result shows that under a confidence level of 90%, the removal efficiencies of fine particles are statistically significantly higher than those of coarse particles. Under negative voltages, the average removal efficiencies for the fine particles (48–83%) are higher than those for coarse particles (24–78%) except at 50 kV, with a confidence level of 90% under the same t-test. This result is expected of the ESPs, as they are generally designed to be more effective for fine particle collection. On the other hand, larger particles tend to be more difficult to sample in turbulent flow as they do not follow the flow as well as smaller particles. Whether this is a sampling artifact or voltage sensitivity requires further investigation.

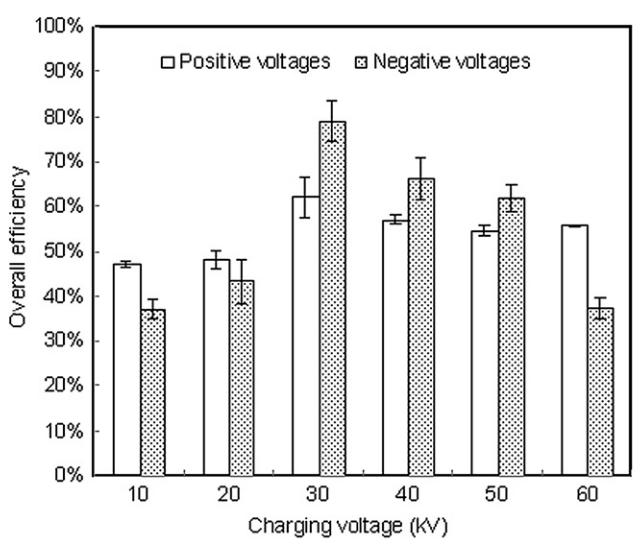

Fig. 3. Overall particle collection efficiencies under positive and negative charging voltages.

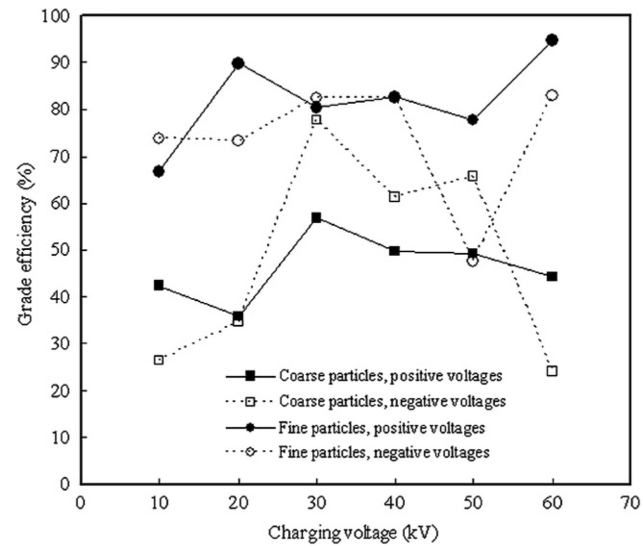

Fig. 4. Grade efficiencies of coarse and fine particles under positive and negative charging voltages (coarse particles: diameter larger than 2.1 μm; fine particles: diameter less than or equal to 2.1 μm).

3.3. Corona power

The overall efficiency as a function of corona power is presented in Fig. 5. The results of positive voltages and negative voltages

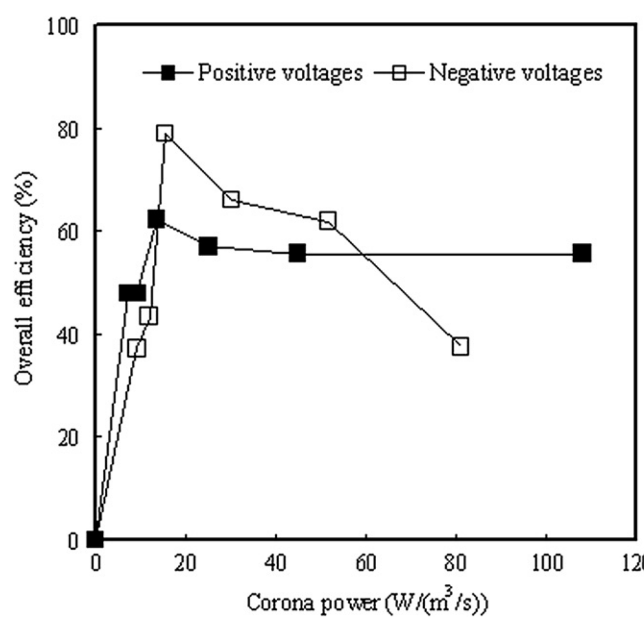

Fig. 5. Overall particle collection efficiencies based on corona power.

showed good agreement. The overall dust removal efficiencies increased sharply when the corona power increased from 0 to 13.5 W/(m^3/s) for positive voltages and from 0 to 15.3 W/(m^3/s) for negative voltages. Then the efficiency decreased with corona power increasing. The increasing trend at low corona power is consistent with some earlier studies [11,22], which indicated that higher charging voltages help increasing the dust removal efficiency. However, the decreasing trend under high corona power may be due to the stronger corona winds produced, which can cause the re-entrainment of the collected particles back to the gas stream [19,20]. This reason might be the same as the lower overall efficiency under high charging voltages.

3.4. Energy consumption per unit particle removal

Table 3 shows the power consumed at various voltages. In spite of the high voltage applied, the current is very low (mille amperage), which result in low power consumption. The power consumption is less than 12 W for the highest voltage applied, which is less than that of a light bulb. This is also consistent with the ESCS system (about 15 W) reported earlier [13].

The energy consumption per unit particle removal is also estimated using the following eq. (3):

$$E_{C/m} = \frac{P}{\eta_T \times r \times Q} \tag{3}$$

where, $E_{C/m}$ is the energy consumption per unit particle removal (J/mg); P is the consumed power (watt) of iESP, which is calculated by $P = I \times U$; I is the current (mA) measured in the iESP; U is the voltage (kV) applied to the iESP; C is feeding concentration of particles (mg/m^3); Q is flow rate (m^3/s), which was 0.111 m^3/s in this study.

Fig. 6 shows the energy consumption per unit particle removal. The trends of energy consumption are almost similar for both positive and negative voltages. Under high voltages (40, 50 and 60 kV), the energy consumption is at least twice more than the ones under low voltages (10, 20 and 30 kV). Higher voltage is associated with higher power consumption and hence higher cost, however, it is not necessarily associated with higher control efficiency. The consumptions under low voltages remain consistent from 1.1 to 3.3 J/mg. This result indicated the optimum for PM removal and energy consumption may be in the 10–30 kV range, for negative corona. This is in good agreement with the overall PM removal efficiency estimated above.

3.5. Comparison with industrial ESP

Some parameters of ESPs are listed in Table 1 to compare the iESP with industrial ESPs [23]. The iESP has a much higher Reynold number and a much shorter flow residence time than the industrial ESP, which is widely used for dust control [23,24]. The collection efficiency achieved (79%) is excellent considering the very low specific collection area which is an order of magnitude less than that of industrial scale units. This is an indication of the efficiency of charging and collecting sections in the design. The iESP is more energy efficient as indicated by the very low power ratio. The cost of this prototype unit is approximately $6000, which is comparable with the ESCS system of $4000 [14]. The cost is expected to be much lower if commercialized due to bulk production.

Table 3
The power consumption of the iESP at various test voltages.

Voltage (kV)	Positive voltages		Negative voltages	
	Average current (mA)	Power (Watt)	Average current (mA)	Power (Watt)
10	0.08	0.8	0.10	1.0
20	0.05	1.0	0.067	1.33
30	0.05	1.5	0.05	1.5
40	0.07	2.8	0.083	3.33
50	0.10	5.0	0.115	5.75
60	0.20	12.0	0.15	9.0

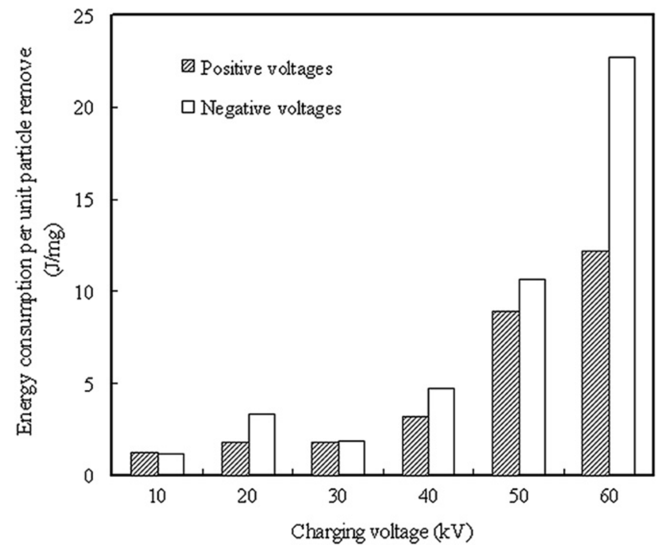

Fig. 6. Energy consumption per unit particle removal (unit: j/mg).

3.6. Real world application

Unlike the industrial exhaust gas which can be consolidated into one system, the exhaust from poultry CAFO are more distributed: most barns have multiples fans instead of one central inlet or outlet. Therefore it may be desirable to design and install CAFO-ESPs in a "distributed" manner, such as installing a simple unit behind a single fan. Poultry barns generally have many fans in one building and each one is about 121.92 cm × 121.92 cm as a very typical size. One iESP unit can be installed in the ducts after the fan.

These fans do not operate all the time (sequential operation) and it would be a good practice to only install the ESPs in the most often operated fans. In the future, the iESP will be designed to turn on only when the fan is on, to further lower the operating cost. The iESP for the poultry dust control needs to be custom designed based on the unique flow patterns and dust characteristics of the facility, in order to achieve the optimum balance of cost and dust control efficiency.

The motivation of this study was to help the CAFOs to meet the dust emission requirements. The design presented in this paper could help reduce the concentration of dust in exhaust, and reduce the adverse effects on environment and neighborhood. However, it will not reduce the concentration of dust inside the barn. A field test should be performed before commercialization.

4. Conclusion

An improved electrostatic precipitator has been designed for the removal of dusts in poultry farms. In this study, corn starch was used instead of real poultry dusts to evaluate dust removal efficiency. The collection efficiency ranged from 37% to 79% under various positive and negative voltages, and the maximum removal efficiency occurred under −30 kV. This device has higher efficiency (45–95%) in controlling fine particles. The power consumption is less than 12 W for all the conditions, which is as low as a light bulb.

The energy consumption per unit particle removal confirmed that the most cost effective operation is in the 30 kV range instead of higher voltages. This iESP can handle more turbulent flow at much lower residence time than the conventional industrial ESPs. Besides technical feasibility, this device also has high economic feasibility.

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