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Field Evaluation of an Electrostatic Air Filtration System for Reducing Incoming Particulate Matter of a Hen House

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ABSTRACT. *As a result of the 2015 unprecedented high pathogenic avian influenza outbreak in the United States, some egg producers in the US started to use inlet air filtration to reduce the risk of disease transmission into hen houses through air route. Removal efficiency of particulate matter (PM), the carrier of airborne pathogens, by such filtration systems has not been investigated. This field study was, therefore, conducted to evaluate the PM removal efficacy by an electrostatic air filtration system (consisting of a low-grade air filter and an electrostatic particle ionization or EPI system) installed at the inlet of a commercial high-rise hen house. Evaluation was performed in two test rounds over one-year period. Results show that average PM removal efficiencies in rounds 1 (spring to summer) and 2 (late fall to spring) were respectively 66% and 29% for PM₁, 66% and 30% for PM_{2.5}, 66% and 31% for PM₄, 68% and 36% for PM₁₀, and 68% and 45% for total PM. Removal efficiency became unstable when the EPI system was inactivated (i.e. when solely relying on the filter for PM removal). House static pressure and ventilation rate indicated considerable clogging of the filter media by dust accumulation and the need for replacement after ~16 weeks of use in spring-to-summer time (round 1); however clogging was not an issue during the entire late fall-to-spring sampling period (round 2, 24 weeks). Appearance of the filter changed gradually as dust accumulated with time, which can be captured by image analysis and used to judge filter dirtiness and lifespan. Findings of this field study provide insight into the efficacy of PM removal by such a low-cost air filtration system, which will help egg producers in their decision-making for disease prevention strategies.*

Keywords: filtration, electrostatic particle ionization, particulate matter, reduction, hen house

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1. INTRODUCTION

Disastrous high pathogenic avian influenza (HPAI) outbreak in the United States in 2014-15 resulted in tremendous losses to the poultry industry. In less than 7 months (December 2014 to June 2015), 232 farms in 15 states and over 50 million birds were affected (USDA, 2016), translating an overall economic loss of \$3.3 billion (Greene, 2015). The outbreak was eventually under control, but its impacts lasted longer as farm disinfection, restocking, and governmental subsidy took time to be implemented. Many lessons were learnt during this outbreak, while the transmission mechanisms that led to fast disease spreading among farms remained fully understood. Clearly, traditional biosecurity protocols (e.g., restricting site visit, performing entrance disinfection, and wearing biosecurity gears) for preventing direct-contact or mechanical transmission were not fully successful to stop the outbreak. Airborne transmission – a mechanism that majority of virus is carried by particulate matter (PM) and transported in/by air (Cambra-López et al., 2010) – has been receiving increasing concerns. Air samples were taken in and nearby the infected houses and were tested positive with HPAI viral genetic materials (Torremorell et al., 2016). Implications of air transmission during the outbreak also include anecdotal observations showing that the initial high bird mortalities occurred near the air inlets of poultry houses, and meteorological analysis revealed that many infected farms received air from previously-infected sites (Zhao et al., unpublished). Although there is no direct evidence supporting long-distance airborne transmission among farms at this moment, a few egg producers have started using air filtration systems to prevent airborne AI virus from entering their hen houses.

Inlet air filtration systems have been practiced by swine industry in order to minimize airborne transmission of porcine reproductive and respiratory syndrome (PRRS) virus. The filter media used in swine houses typically have small pore sizes and high minimum efficiency reporting values (MERV), e.g. MERV 14-16. Several pilot-scale studies showed that risks of PRRS infection were significantly reduced by filtering the incoming air (Batista et al., 2010; S. Dee et al., 2005; S. A. Dee et al., 2006). Field applications of these filters in commercial swine houses were also proven to be effective and economically-sound (Alonso, Davies, et al., 2013; Batista et al., 2009). However, the filtration systems for swine houses may not be applicable to poultry houses because of differences in compositions of air for these two environments. Air for poultry environment is generally abundant with PM originating from feather, feed and dry manure particles (Aarnink et al., 1999). The dusty air could easily clog filter media, especially for those with small pore sizes and high MERV grades. Clogging of filter may compromise house ventilation and require frequent filter replacement, therefore increasing the investment and payback time, making high MERV filters impractical in poultry applications. Instead, filters with larger pore sizes and lower MERV grades may offer an alternative for poultry houses because these filters provide less restriction to air flow. Although the PM removal efficiency by low MERV filters is lower than that on high MERV ones, it may be improved by combining other promising PM precipitation technologies, e.g., electrostatic particulate ionization (EPI).

Electrostatic particulate ionization technology has been used to reduce PM and airborne pathogen concentrations inside animal houses (Cambra-López et al., 2009; Ritz et al., 2006). The EPI system consists of a power supply, corona pipe/wire, motorized winch and a high voltage switch. Operated at a high voltage (~30 kV), the corona pipe/wire keeps releasing large amount of negative ions into the air. The ions collide with airborne particles, polarizing them and making them attached to each other and deposit to any surfaces. For EPI application in poultry housing, the study performed by Ritz et al. showed that PM was reduced by 43% in broiler houses when EPI systems were used (Ritz et al., 2006). Cambra-López et al. (Cambra-López et al., 2009) reported 36% and 10% reductions for PM₁₀ and PM_{2.5} in broiler houses by EPI systems. The performance of a combined system, i.e. EPI and low MERV filter, on PM removal at air inlets of poultry houses has not been evaluated.

To explore the application of inlet air filtration in poultry houses and provide insights on its potential to minimize airborne transmission of AI, this study aims to 1) evaluate efficiencies of an electrostatic air filtration system on PM reduction in incoming air of a high-rise hen house over a course of one year; 2) monitor building static pressure (SP) as an indicator of ventilation restriction by the air filtration system. Air temperature, relative humidity (RH) and carbon dioxide (CO₂) levels were also monitored. Appearance of used filter was compared with the clean filter through image analysis, which was used to determine the filter dirtiness and lifespan.

2. Materials and Methods

2.1 Experimental hen house

An east-west oriented high-rise hen house (L×W×H=180×18×6 m) with a nominal capacity of 100,000 birds was used as the experimental house in this study. Six side-by-side cage rows were aligned lengthwise in the house. Each cage row had five-tier stacked cages. The stocking density was 516 cm²/hen. The house used a negative pressure ventilation system. Ambient air entered the house through eave inlets on both north and south side walls. Forty 1.2-m exhaust fans at the lower level of the house (20 fans in the north wall, and 20 fans in the south wall) were automatically controlled ON or OFF to maintain target indoor thermal environment.

2.2 Electrostatic air filtration system

The electrostatic air filtration system was installed along both north and south eave air inlets (Figure 1). The 1.2-m wide MERV-8 filters (Clarcor Ultra II, Air Technologies Inc., Ottawa, KS) were used to cover the entire eave inlets. An EPI system (Baumgartner Environics, Inc., Olivia, MN) was installed to charge particles in the incoming air, which aimed to improve the PM removal efficiency. The corona wires with sharp point electrodes were suspended to the triangular drop-off supports and were positioned at a 0.6 m distance in parallel to the filter media. The corona wires could be lifted by pushing up the triangular drop-off supports. This design eases replacement of filter media at the end of its lifespan. The EPI system was operated at high voltage (-30 kV) but low and safe current (2 mA).

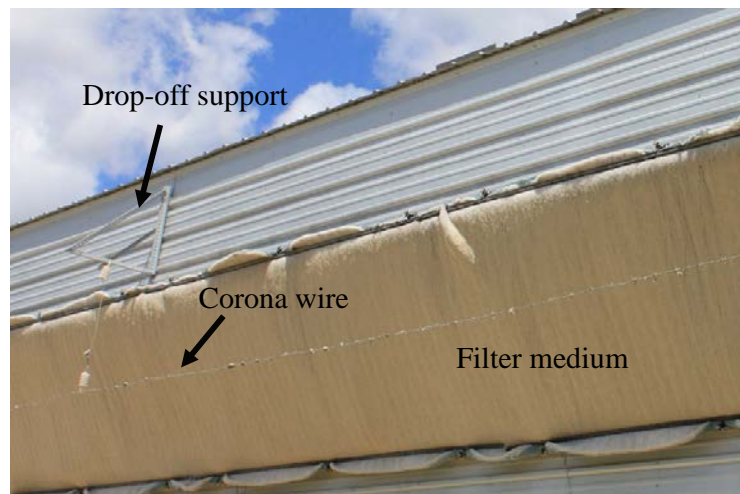


Figure 1. A picture of the electrostatic air filtration system installed at the eave air inlets of the experimental laying-hen house.

2.3 Measurement

Particulate matter removal efficiencies of the electrostatic air filtration system and environmental parameters were monitored in two rounds, covering different seasons of the year. A new batch of filter media was used in each round. The first batch of filter media was installed on March 5, 2016 and removed in the week of July 6, 2016; and the second batch of filter media was installed on November 10, 2016 and monitored continued till April 29, 2017. Laying hens in the experiment house were 33 weeks old on March 5, 2016.

Table 1. Summary of measurements

Parameter	Sampling period	Frequency	No. of locations	Sampling interval
Particulate matter	4/3/2016-7/5/2016 (round 1)	Every 2-3 weeks (round 1)	4	15 s (for 5 min at each location)
	12/28/2016-4/29/2017 (round 2)	Every 2-5 weeks (round 2)		
Temperature	3/23/2016-7/24/2016 (round 1)	Continuous	10	10 min
	12/12/2016-4/29/2017 (round 2)			
Relative humidity	3/23/2016-7/24/2016 (round 1)	Continuous	10	10 min
	12/12/2016-4/29/2017 (round 2)			
Static pressure	4/3/2016 – 4/29/2017	Continuous	1	1 min
CO ₂	4/23/2016 – 4/29/2017	Continuous	2 (1 composite)	1 min
Images	3/5/2016-7/5/2016 (round 1)	Every 2-3 weeks (round 1)	4	-

Particulate matter, housing static pressure (SP), indoor/ambient temperature, indoor/ambient relative humidity (RH), and carbon dioxide (CO₂) concentrations at stage-1 exhaust fans were measured in this study. It was planned to monitor PM every two weeks. However, site visit had to be adjusted due to occasional man-lifter malfunction and extreme weather conditions. Eventually, PM concentrations were measured every two to three weeks in round 1 and two to five weeks in round 2. Static pressure, temperature, RH and CO₂ were continuously monitored at respective intervals (Table 1). To check filter dirtiness through image analysis, pictures of the filters were taken every two to three weeks in round 1. A summary of the measurements is listed in Table 1.

Particulate matter (PM)

A portable Dusttrak 8533 optical monitor (TSI Incorporated, Shoreview, MN) was newly procured and used to monitor PM concentrations. The PM monitor can simultaneously quantify the real-time mass concentrations of five size fractions (PM₁, PM_{2.5}, PM₄, PM₁₀, and total PM) in the range of 0.001 – 150 mg/m³ at programmable intervals. Manufacturer calibration was performed before and after the year-round measurement.

PM concentrations were measured at four locations (i.e. ¼ and ¾ length of the south and north eave inlets) on each sampling day in this study. At each sampling location, PM were measured at both upstream and downstream of the filters. Each measurement lasted 5 min at 15 s intervals. An antistatic rubber tubing (provided with the Dusttrak) was attached to the air inlet of the PM monitor, allowing for measurement of downstream PM concentration by inserting the free tubing end to the other side of the filter through a small hole. A wooden support was built to accommodate the PM monitor. Figure 2 shows the PM sampling system and access to the filter using a man-lifter.

As human activity may agitate surface particles suspending into the air, thus affecting PM measurement, 5-min settlement time were given before all measurements started. A distance (1 m) between the investigators and the monitor was kept during the settlement time and measurement to minimize potential interferences. The EPI system remained activated during the PM measurements. To demonstrate how the EPI system improves system performance, PM removal efficiencies with the EPI inactivated vs. activated were compared.

Temperature and relative humidity (RH) measurements

Temperature and RH were measured at eight inside locations and two outside locations using HOBO Pro V2 sensors (Onset Computer Corp, Bourne, MA). All sensors were calibrated at Iowa State University before commencement of the experiment. The HOBO Temp/RH sensors for the inside measurements were placed next to the existing house temperature sensors, and were logging data at 10-min intervals.

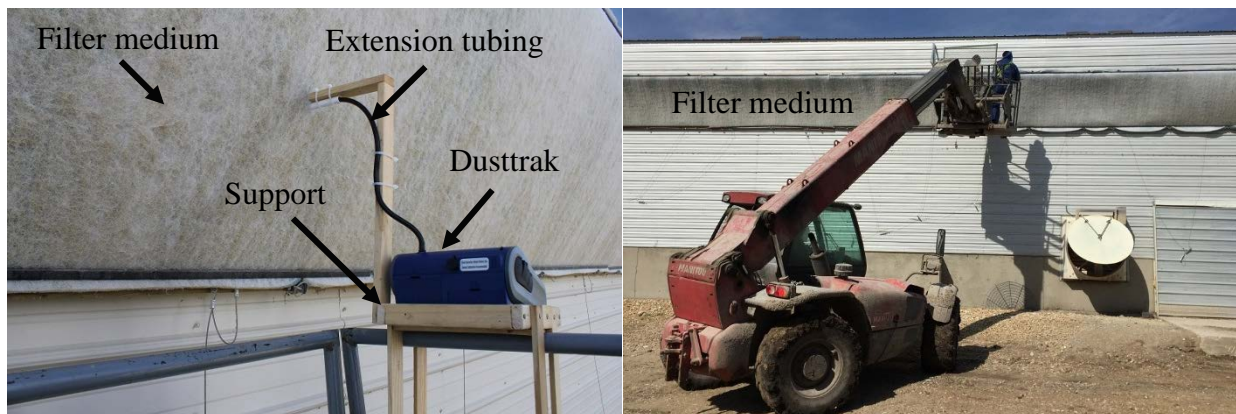


Figure 2. Particulate matter sampling system (left) and accessing to sampling locations via a man-lifter (right).

Building static pressure (SP) measurement

Building static pressure (SP) was measured with a Setra sensor (Model 264, 0-0.5" WC, Setra Systems, Boxborough, MA). Current outputs of the SP sensor were recorded by a 4-channel HOBO data logger (UX120-006M, Onset Computer Corp, Bourne, MA) at 1-min intervals. The SP sensor was calibrated using a manometer (Model MARK II 25, 0-3" WC, Dwyer, Michigan City, IN) before experiments started.

Carbon dioxide (CO₂) measurement

Carbon dioxide concentrations in the hen house were continuously measured using a CO₂ transmitter (GMT 220, range 0-10,000 ppm, Vaisala Inc., Eagan, MN) installed in a portable measurement unit (PMU). The internal air pump of the PMU drew air samples at two stage-1 exhaust fans. The air samples then composited into one sample that was analyzed for CO₂ concentration by the transmitter. Detailed descriptions of the PMU system have been provided by Xin et al. (2003). The transmitter was calibrated using zero gas (ultra-high pure nitrogen, 99.999%, Praxair, Danbury, CT) and span gas (3100 ppm CO₂ with N₂ balance, Praxair, Danbury, CT) at beginning of the experiment. A 4-channel HOBO data logger recorded the data at 1-min intervals.

Ventilation rate (VR) of the house was estimated using CO₂ balance method (Li et al., 2005; Liu et al., 2016; Pedersen et al., 2008). In high-rise hen house, CO₂ is produced from hen respiration and manure storage. Production of CO₂ by the hens was calculated based on the hens' body weight and their bioenergetics values, i.e., specific total heat production rate (THP) and respiratory quotient (RQ), as reported by Chepete et al. (2004). Production of CO₂ by the manure in the storage

was estimated to be 0.0315 mL/s/[m² floor area] per cm of manure depth. Starting from 18 weeks of age, the increase of manure thickness was assumed to be 0.35 cm per day (Zhao et al., 2013). Detailed description on VR calculation was provided by Zhao et al. (2013). All manure in the storage was cleaned out annually in mid-September.

Filter image analysis

Checking the dirtiness appearance of the filter could be a quick and easy way to determine the remaining lifespan of a filter. The dirtiness appearance of the filter could be reflected by the grayscale of the filter in an image. In grayscale images, gray colors are assigned to values of 0-255 with “black” and “white” being 0 and 255, respectively. Other gray colors have values in-between, depending on their darkness (the darker the color, the greater value). Appearance of a new filter becomes darker (i.e. color code in grayscale image increases) as PM continuously accumulates in the filter. When the filter surface is smeared by PM, it may appear as the PM color.

During round 1, filter images were taken at four locations (same as the PM measurement locations) using a Canon EOS-550D camera. The images were converted to grayscale, and the grayscale values of the filter were obtained using image analysis in Matlab (R2013a, The MathWork Inc. Natick, MA). In order to eliminate the possible interference by ambient light that varied temporally and spatially, a piece of new filter was placed aside the used one under assessment, and served as reference in the image analysis. The ratio of the grayscale values between used and new filters was calculated and used as the parameter for dirtiness evaluation. The range of the ratio is 0 – 1, with a greater value indicating a cleaner filter.

3. Results and Discussion

3.1 Temperature and relative humidity

Figure 3 shows the daily mean ambient and indoor temperature and RH during rounds 1 and 2. With ambient temperatures varying between -22.7°C and 29.5°C, daily mean indoor temperature was generally maintained within animal thermoneutral zone. The mean (\pm standard deviation) and max indoor temperatures were 24.2°C (\pm 2.4°C) and 31.3°C, respectively. Indoor RH remained relatively stable around 80% in early stage of round 1, but fluctuated more in late stage. For round 2, indoor RH was maintained at around 70%. It should be mentioned that both indoor temperature and RH values reported in this study were measured at bird levels (sensors were installed in empty cages adjacent to those with hens), thus reflecting the thermal environment sensed by the hens.

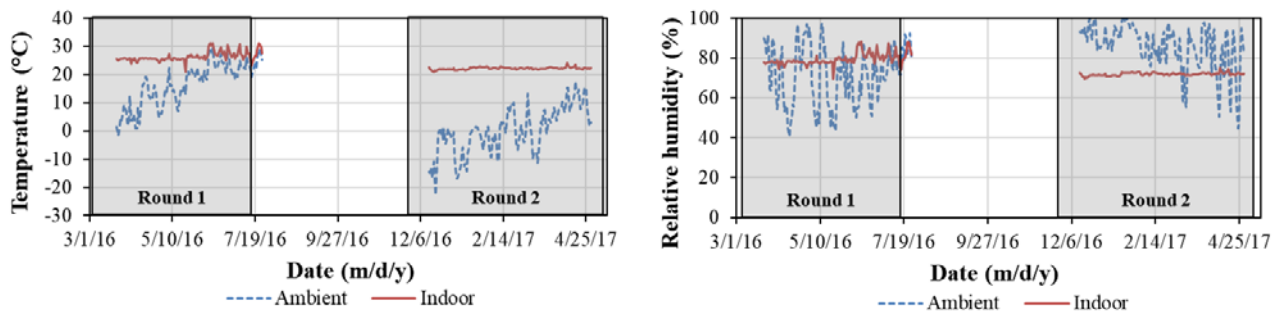


Figure 3. Daily mean ambient and indoor temperature and relative humidity. Ambient data were the average readings of two sensors, and indoor data were the average readings of eight sensors.

3.2 Particulate matter (PM) concentration

The PM concentrations were generally below 0.15 mg/m³ during round 1 test. Figure 4 shows the average PM concentrations of the four measurement locations on each sampling day in round 1 test. The average upstream and downstream PM concentrations were 0.017 and 0.005 mg/m³ for PM₁, 0.018 and 0.006 mg/m³ for PM_{2.5}, 0.020 and 0.010 mg/m³ for PM₄, 0.036 and 0.006 mg/m³ for PM₁₀, and 0.059 and 0.015 mg/m³ for total PM, respectively. Figure 5 shows that the average upstream and downstream PM concentrations in round 2 were 0.201 and 0.148 mg/m³ for PM₁, 0.204 and 0.149 mg/m³ for PM_{2.5}, 0.209 and 0.151 mg/m³ for PM₄, 0.243 and 0.160 mg/m³ for PM₁₀, and 0.299 and 0.169 mg/m³ for total PM, respectively.

Particulate matter concentrations measured in late fall-to-spring round (round 2) were much higher than those measured in spring-to-summer round (round 1). After emitting from the hen house, dispersion of PM in atmospheric boundary layer is driven by the buoyancy force. Buoyancy effect is greater under warmer weather conditions because the (warm) air at ground level has low density that promotes vertical air turbulence and helps dispersing PM emission to the atmosphere (Stull, 2012). In contrast, air is dense and less turbulent under cold weather conditions, therefore the PM emission tended to accumulate nearby the source. Another possible contributor, though less likely in this case, to the difference in PM concentration between rounds could be condensed droplets in exhausted air that affected the readings of the PM monitor

(Cambra-López et al., 2015; Heim et al., 2008). The condensation occurred when the indoor warm and humid air was exhausted and cooled down to the dew point temperature in winter time. The PM monitor used in this study was an optical monitor that records total amount of solid particles and droplets. As a result, compositions of PM measured in warm and cold weather conditions could have differed. Figure 6 shows a clear negative correlation between upstream PM concentration and ambient temperature. Besides effect of air temperature on PM dispersion, another reason for this inverse relationship stems from the increased ventilation rate, thus more dilution to the emitting PM quantity, as ambient temperature rises.

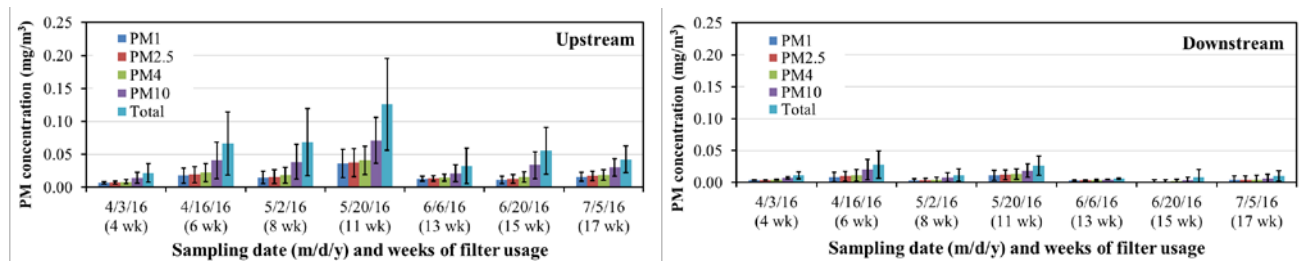


Figure 4. Particulate matter concentrations (mean \pm SD, n=4) in upstream and downstream air of the electrostatic filtration system in round 1 test.

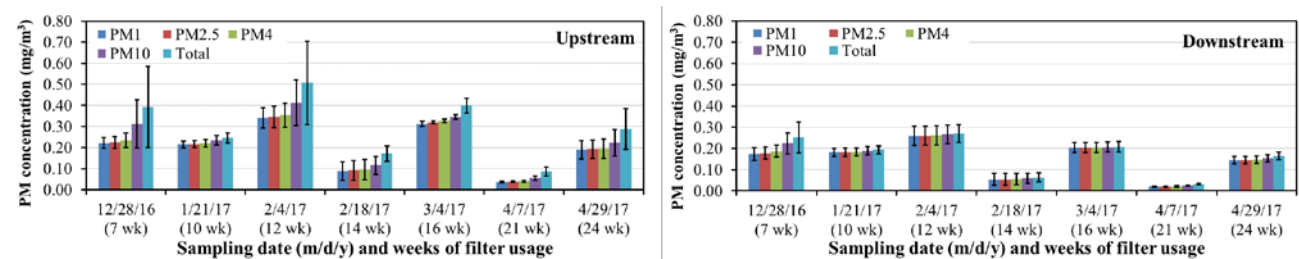


Figure 5. Particulate matter concentrations (mean \pm SD, n=4) in upstream and downstream air of the electrostatic filtration system in round 2 test.

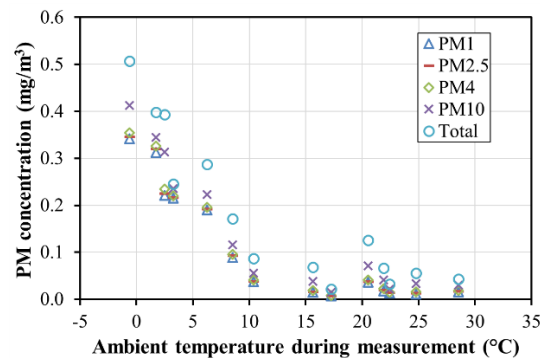


Figure 6. Upstream particulate matter concentrations measured at different ambient temperature.

3.3 Particulate matter (PM) removal efficiency

The average PM removal efficiencies in rounds 1 and 2 were 66% and 29% for PM₁, 66% and 30% for PM_{2.5}, 66% and 31% for PM₄, 68% and 36% for PM₁₀, and 68% and 45% for total PM, respectively. Numerically, removal efficiencies were greater for larger sizes of PM because larger particles tend to settle and are easier to be intercepted and impacted in the filter media (Boskovic et al., 2005). Furthermore, larger particles are given adequate charge to enable them to be captured better compared to small ones (Zhang, 2004). The minimal requirements of PM removal efficiencies by filters with varying MERV levels have been reported by American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE, 2015). The MERV 8 filter should provide no less than 20% reduction for 1-3 μ m particles, and no less than 70% for 3-10 μ m particles. The reduction results in this study cannot be directly compared with the ASHRAE standards because the size categories are different. Also, ASHRAE values set forth standards for reduction efficiency tested under laboratory conditions that are relatively stable. In this study, the filtration system was tested in field conditions, therefore, its removal efficiency may be affected by variable ambient environments, such as wind, temperature, humidity, dust loading rate, etc. Inlet air filtration systems have been practiced in swine houses to prevent airborne transmission of PRRS virus. Interests of related research focused on examining effectiveness in disease control (Alonso, Murtaugh, et al., 2013; S. A. Dee et al., 2006; Spronk et al., 2010), rather than evaluating the actual particle removal efficiency of the filtration system. This study provides information of in-situ PM reduction by low MERV filter coupled with electrostatic system at an animal house. The

electrostatic filtration system, to some extent, would help to prevent airborne transmission of avian influenza because infection risk is positively related to the amount of virus-laden particles entering the animal houses (Garner et al., 2006). Further validation using animal model is needed.

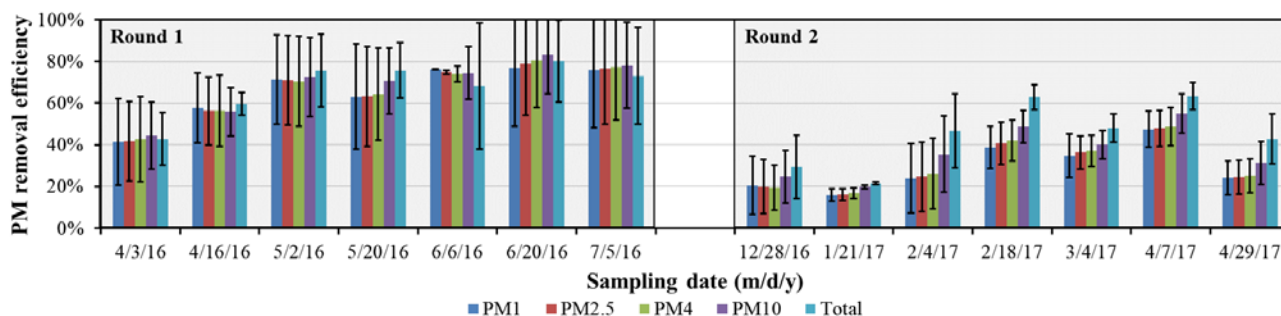


Figure 7. Particulate matter removal efficiency by the electrostatic filtration system. Error bars represent standard deviation (n=4).

Figure 7 shows the PM removal efficiencies by the electrostatic filtration system on each sampling day. In round 1, the average PM removal efficiencies seemed to increase gradually from 4/3/16 (4 weeks of filter age) to 5/2/16 (8 weeks of filter age), then plateaued till the end of the sampling period. Similar trend in temporal PM reduction was also noticed in round 2 between 12/28/16 (7 weeks of filter age) and 4/7/17 (21 weeks of filter age). The PM removal efficiencies dropped on the last sampling day in round 2, but were still comparable or higher than the values measured on the first two sampling days in the same round. The results indicate that the dust accumulation on the filter media, to some extent, might have decreased the filter porosity and permeability (Kanaoka & Amornkitbamrung, 2001), thereby improving their PM reduction efficiency. Particulate matter removal efficiency by electrically charged filter media, or so-called electret filter, has been extensively investigated. In general, the PM removal efficiency by these filters gradually degrade as particles are loaded on the filter media because of the neutralization of charges on the fiber and screening of the filter charge (Brown et al., 1988; Ji et al., 2003; Walsh & Stenhouse, 1997). Instead of directly charging the filter media, the electrostatic filtration system in this study continuously charged the particles in the upstream air of the filter. As dust does not accumulate on the charging system, the charging performance would not be affected, which helped to maintain the PM removal efficiency over time (Chai et al., 2009).

It is necessary to check the PM reduction behavior of the electrostatic filtration system when the EPI was inactivated (thus no electrostatic charge, or filter alone). To that end, PM removal efficiency was evaluated on 6/20/16 with EPI system ON vs. OFF. On average, PM could still be reduced by 40-50% when the EPI was turned OFF (Figure 8). However, the filtration efficacy became less consistent as indicated by large standard deviations. PM reduction for two out of the four sampling locations were found to be negative, meaning higher PM concentrations were measured in the downstream air than in the upstream air. The results thus indicate the need of proper EPI operation together with filter in order to ensure a consistent PM removal.

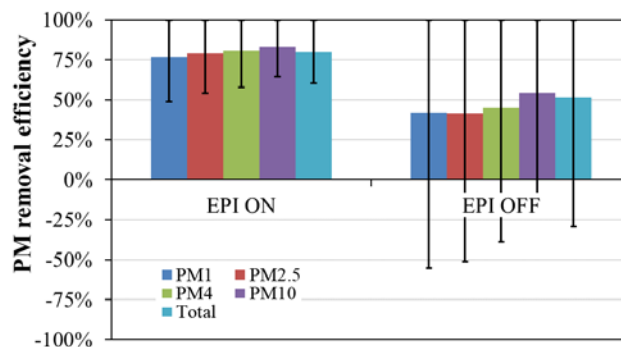


Figure 8. Particulate matter (PM) removal efficiency by electrostatic filtration system with vs. without operating the electrostatic particle ionization (EPI) component. Measurement was performed on 6/20/2016. Error bars represent standard deviations (n=4).

3.4 Static pressure

High SP may overload exhaust fans, thereby reduce air movement and compromise housing ventilation. For animal housing systems, SP is typically maintained in the range of 12-30 Pa, and SP above 50 Pa should be avoided. As dust accumulates, the inlet filter would eventually restrict housing ventilation at certain point of time. The restriction can be

reflected by the SP. The daily mean housing SP since beginning of the measurement is shown in Figure 9. Daily mean SP in round 1 was generally maintained within the acceptable range before mid-June, 2016. During this period, SP varied between 15 and 40 Pa. The SP started to increase after mid-June, which could be due to a combined effect of dust accumulation on filter and warm weather that requires high air exchanges. In late June and early July (6/27/16 – 7/5/16), SP continuously increased and exceeded acceptable level of 50 Pa, indicating that the filter media need for replacement. The filter was then taken down the following two days, 7/6/16 and 7/14/16. Significant drops in SP were noticed after the filter was taken down. Ambient and indoor temperature difference (ΔT) was plotted together with SP on a few days before, during and after clogged filter from 6/10/16 to 7/12/16 (Figure 10) when the ambient temperatures were between 18.6 and 29.5°C. A spike of ΔT was clearly shown during the clogging period which was due to ventilation restriction and accumulation of the extra heat in the house. The result shows that ΔT could be 7-8 °C when SP was above 50 Pa. In round 2, SP was generally below 40 Pa, and clogging was not noticeable.

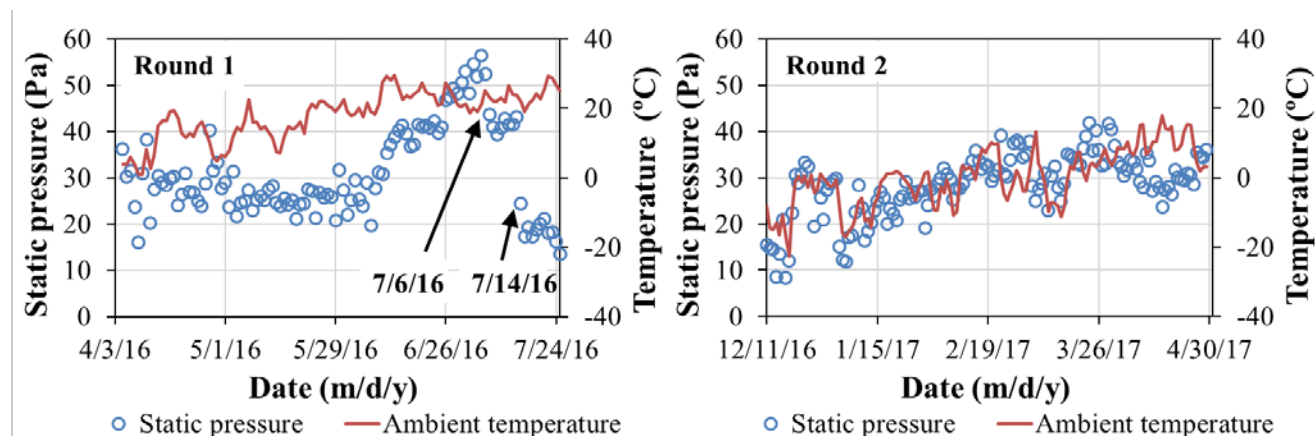


Figure 9. Daily mean static pressure of the high-rise hen house.

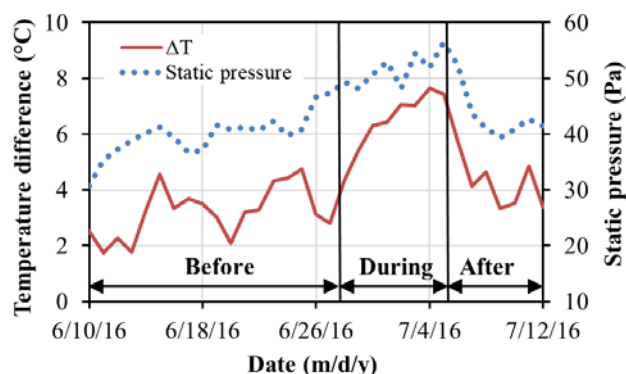


Figure 10. Ambient and indoor temperature difference (ΔT) and static pressure on a few days before, during and after clogging (6/10/16 – 7/12/16).

3.5 Carbon dioxide concentration and ventilation

Daily mean CO_2 concentrations in the hen house are shown in Figure 11. The CO_2 concentrations were in range of 600 – 2000 ppm in round 1, and 800 – 3700 ppm in round 2. Carbon dioxide concentration generally has a negative correlation with ambient temperature in animal housing and reflects proper functioning of ventilation system (Xin et al., 2009; Zhao et al., 2015). Egg producers empirically target indoor CO_2 concentration below 5000 ppm, as a higher concentration indicates under-ventilated environment where the occupants (animals and caretakers) may experience humid air and high concentrations of ammonia, odor and microorganisms. In this study, the CO_2 concentrations were all below 5000 ppm, even on extreme cold days (ambient temperature < -20°C) in round 2. Carbon dioxide concentrations in summer time were comparable to those reported in hen houses without inlet filtration systems (Zhao et al., 2015).

Carbon dioxide balance (or indirect calorimetry) method is an affordable and simple way to estimate VR of animal houses, and it produces acceptable VR results (Li et al., 2005; Xin et al., 2009). Daily mean VRs estimated using CO_2 balance method are shown in Figure 12. The VRs were between 1.0 and 12.0 $\text{m}^3/\text{h}/\text{hen}$ in round 1, and between 0.6 to 5.5 $\text{m}^3/\text{h}/\text{hen}$ in round 2. The VRs of the high-rise hen house were comparable to those reported in other types of hen houses, e.g. aviary, conventional and enriched colony, in the Midwestern US (Zhao et al., 2015; Zhao et al., 2013). During the period of filter clogging in round 1 (6/27/2016 – 7/5/2016), the VR notably dropped while ambient temperature stayed relatively

stable at $\sim 20^{\circ}\text{C}$. This, again, suggests that dust accumulation on filter may restrict ventilation, and producers should pay close attention to the VR or SP when filtration systems are used.

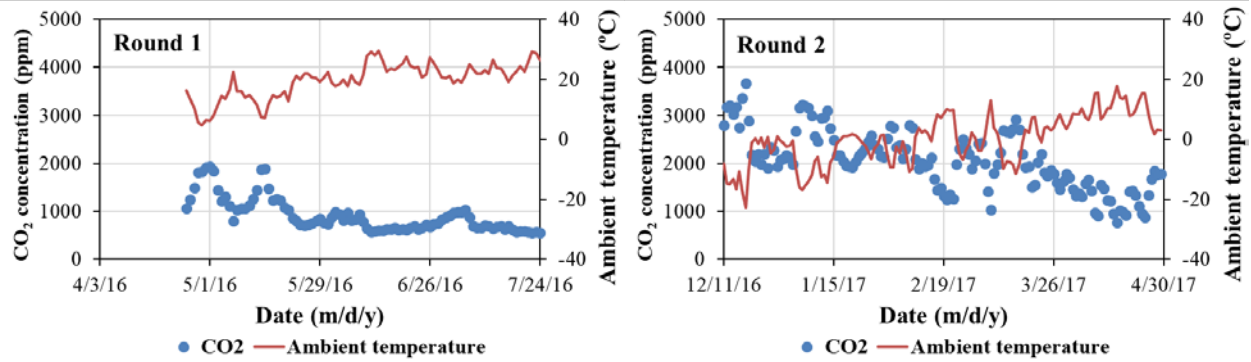


Figure 11. Daily mean carbon dioxide concentration in the high-rise hen house and ambient temperature.

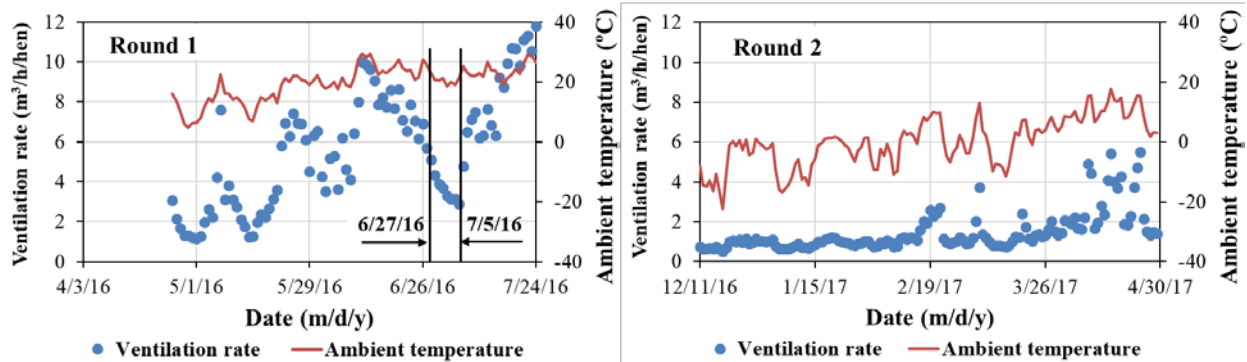


Figure 12. Daily mean ventilation rate in the high-rise hen house and ambient temperature. During the period of 6/27/16 to 7/5/16, the filter had considerable clogging due to PM accumulation.

3.6 Image analysis of filter

Appearance of filter may reflect its dirtiness and even tell the time of replacement. Figure 13 shows the color and grayscale images of new and used filters in round 1. The new filter had clean fibers and appeared light white color. With usage, the filter turned into darker color. The darkest appearance occurred when the filter was used for 8-11 weeks. Thereafter, more dust smeared the surface of the filter, yielding a light yellow color similar to that of dust particles from the hen house. The grayscale ratio of used/new filters derived by image analysis shows similar dynamic of the color change. The grayscale ratio exhibited a quadratic curve over time (Figure 14). The ratio decreased from early stage till 8 – 11 weeks of filter age, then bounced back thereafter. The ratio of week 17 (7/5/16) was 0.76, which was comparable to that of week 4. The filter was clogged in the end of June based on the observations of SP and VR. Therefore, the filter replacement could be carried out at the moment when grayscale ratio bounces back to around 0.70 – 0.75. Our results revealed the possibility of determining filter replacement based on image analysis of the filter appearance.

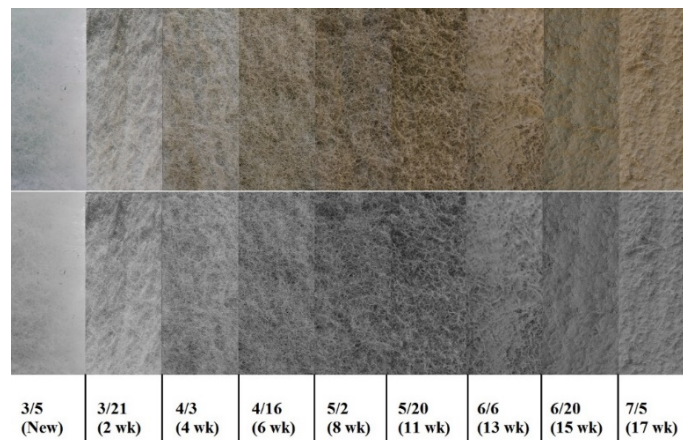


Figure 13. New and used filter in color (up) and grayscale (down) images on each sampling day (m/d, 2016) in round 1. Weeks in parenthesis are the filter age of usage.

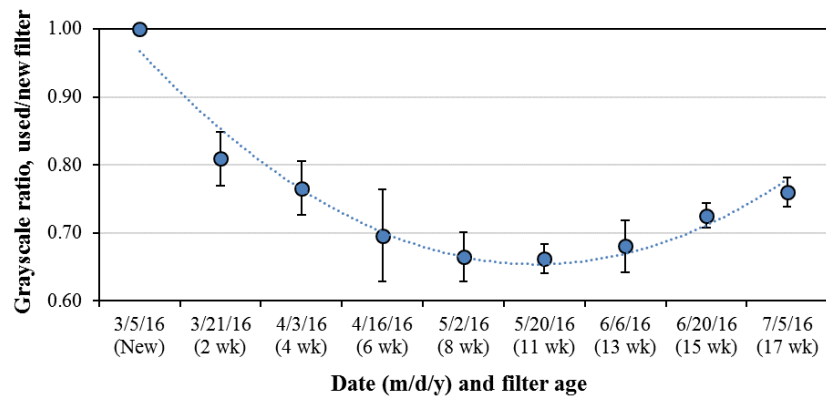


Figure 14. Ratio of grayscale values between used and clean filters in round 1. A lower ratio indicates a dirtier filter (or darker in color). Vertical bars are standard deviation (n=4).

4. Conclusions

In an effort to prevent airborne transmission of avian influenza and other pathogens, egg producers in the US started to use inlet air filtration systems to reduce PM, the carrier of pathogens, entering their hen houses. This study evaluated the PM removal efficiency by an electrostatic filtration system installed at the air inlets of a high-rise hen house over a course of one year. Based on the results of two rounds, we came to the following observations and conclusions.

- Indoor temperature and relative humidity were generally maintained within comfortable ranges during measurement period.
- Average PM removal efficiencies in round 1 (spring to summer) and round 2 (later fall to spring) were 66% and 29% for PM₁, 66% and 30% for PM_{2.5}, 66% and 31% for PM₄, 68% and 36% for PM₁₀, and 68% and 45% for total PM, respectively. Removal efficiency became unstable when the EPI system was inactivated (i.e. relying on the filter alone), making proper operation of the EPI system a necessity to achieve consistent PM reduction.
- Static pressure and ventilation rate showed that the filter media became clogged after ~16 weeks of use in the spring-summer (round 1) cycle, but not so for 24 weeks of use during later fall-spring cycle (round 2).
- Image analysis of the filter appearance could be used to determine the dirtiness and replacement time of the filter media.

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