Quality Assured Measurements of Animal Building Pollutant Emissions: Part 2 -- Particulate Matter Concentrations

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ABSTRACT

Federally-funded, multi-state field studies were initiated in 2002 to measure emissions of particulate matter (PM_{10} and TSP), ammonia (NH_3), hydrogen sulfide (H_2S), carbon dioxide (CO_2), methane (CH_4), nonmethane hydrocarbons (NMHCs) and odor from swine and poultry production buildings in the U.S. This paper describes using the continuous analyzer based on the tapered element oscillating microbalance (TEOM) in these studies to measure PM emissions at identical locations in pair-wise livestock buildings. More frequent maintenance of the TEOM was necessary when used to measure PM concentrations in swine and poultry buildings.

External screens were necessary to prevent rapid plugging of the insect screen in the inlet head. Minute means of mass concentrations exhibited a sinusoidal pattern that followed the variation of relative humidity indicating that the mass concentration measurements were affected by condensation and evaporation of moisture from the TEOM filter. Filter loading increased the humidity effect, probably due to increased adsorption capacity for water vapor. Collocated TEOMs with federal reference method TSP and PM_{10} samplers agreed well when placed near the inlet of exhaust fans in a laying hen house. Initial data showed that average daily mean concentrations of TSP, PM_{10} and $PM_{2.5}$ concentrations at a laying hen house were 1,440 $\mu g/m^3$ (n = 2) 552 $\mu g/m^3$ (n = 4), and 33 $\mu g/m^3$ (n = 1), respectively. The daily mean TSP concentration (n = 1) of a swine house sprinkled with soybean oil was 67% less than an untreated swine house which had a daily mean TSP concentration of 1,143 $\mu g/m^3$. The daily mean ambient TSP concentration (n = 1) between the swine houses was 25 $\mu g/m^3$. Concentrations of PM in swine houses were correlated with animal activity.

Key Words: Dust, sampling, particulate matter, continuous emissions monitoring, quality control, animal housing, multi-state, emission factors, air quality, TSP, PM_{10}, $PM_{2.5}$, abatement, oil sprinkling.

IMPLICATIONS

The management of air pollutants is the next major manure management issue that U.S. agriculture face. Particulate matter (TSP, PM_{10}, $PM_{2.5}$) discussed in this article are emitted by concentrated animal feeding operations (CAFOs) can create animal or human health concerns. Currently, an assessment of the true impact of these pollutants is limited by the lack of reliable data on emission rates. The project goal is to determine baseline emission rates for six types of animal confinement buildings and evaluate the differences in emissions due to geographical region, season of year, time of day, building design, growth cycle of the animals, and building management. In addition, one type of dust abatement technology inside swine barns (i.e., oil sprinkling) is discussed here. Continuous emission and environmental measurements is taken at each facility for fifteen months. To date, this study is the most comprehensive study of air quality in livestock buildings in the U.S. Information from this research will provide producers, technical assistance providers, regulators, and compilers of emission inventories with accurate information.

INTRODUCTION

Although several studies of total suspended particulate concentrations have been conducted, data on emissions of TSP and PM_{10} (10 microns sized particles and under) from livestock buildings are rare.[1,2] It is well established that the emissions are highly variable diurnally and seasonally. Therefore, it is advantageous to be able to measure mass concentrations in real time. Concentrations of mostly PM_{10}, and some TSP and $PM_{2.5}$ were recently measured in a 6-month measurement campaign at a laying hen house in Indiana. Currently, a 6-state USDA study (APECAB) and a 2-state EPA-funded study (CAPESH) are currently quantifying and characterizing baseline emissions of PM_{10}, and TSP from a total of five types of swine buildings and two types of poultry buildings.[3] The objective of this paper is to describe the use of the TEOM for real-time PM concentration measurements at livestock buildings and to present some preliminary baseline concentration data and preliminary data on dust abatement in swine housing using oil sprinkling technology. The secondary objectives were to study the agreement among collocated TEOMs, the effects of filter loading, and the relative magnitude of TSP, PM_{10} and $PM_{2.5}$ concentrations.

EXPERIMENTAL METHODS

The TEOM instrument (TEOM 1400a Ambient Particulate (PM_{10}) Monitor from Rupprecht & Pataschnick) is a continuous PM monitoring device designated by U.S. EPA as an equivalent method (EPA Designation No. EQPM-1090-079) for PM_{10} and used extensively in state and national $PM_{2.5}$ monitoring networks. The acronym TEOM stands for "tapered element oscillating microbalance," an inertial measurement technique that operates on changes in the resonant frequency of an oscillating element as a function of increases in particle mass collected on a filter attached to the element. Changes in the element's resonant frequency are sampled electronically in quasi-real time, providing both continuous and time-averaged measures of mass accumulation that are directly proportional to instantaneous and time-averaged PM mass concentrations in air, respectively. The device operates at an industry-standard, volume-controlled flow rate of 16.7 L/min so that it can be outfitted with a variety of commercially available pre-separator inlets suitable for measuring PM_{10}, $PM_{2.5}$ or any other size fraction of interest. The flow schematic of the TEOM is shown in Figure 1.

At each measurement site in the APECAB and CAPESH studies, a mobile instrument shelter is stationed between two identical or nearly identical, mechanically-ventilated, confined animal production buildings and emission measurements are quasi-continuous. Particulate concentrations are measured with the TEOM at one representative air outlet of each building while simultaneously monitoring total building airflow. Typically, the most representative air outlet is the minimum winter ventilation fan, side by side with an exhaust air sampling point for gas measurement. The sampling locations are inside the building near the inlet of the fans, however, far enough away so that the air velocity around the sampling head is 2 m/s or less. This velocity corresponds to the minimum air velocity in a tunnel ventilated building in the summer.

Housing the TEOMs

The pump and controller unit of TEOM were kept in an instrument shelter to minimize exposure to moisture, PM, gases and debris in animal houses. Figure 2 shows a schematic drawing of one TEOM unit, of which the inlet and sensor unit were located in a swine house, and the main and auxiliary vacuum tubing were heated in a raceway connecting the animal house and instrument shelter. The gas sampling tubing in the raceway were heated and insulated to prevent condensation during cold weather. The swine barn of this study is a mechanically-ventilated building, with all ventilation exhaust fans located at this end of the building.

Figure 3 shows the two collocated TEOMs in the manure storage pit of a high-rise laying hen house, located in front of a minimum ventilation fan. A wooden manure wall was used to keep the TEOM and other devices protected from an accumulating manure windrow. There was no ambient PM measurement in this project and only PM_{10} was measured most of the time. However, there were several TSP and $PM_{2.5}$ measurement trials involved near the end of the study. The study began with one PM_{10} unit and later in the study, three other TEOMs were collocated with the first unit. The objectives were to study the agreement among collocated TEOMs, the effects of filter loading, and the relative magnitude of TSP, PM_{10} and $PM_{2.5}$ concentrations.

Collocated TEOM Units. Two to four TEOMs were used to compare the agreement between TSP and PM_{10} concentration measurements. One set of two TEOMs was collocated at one side of the minimum ventilation fan and measured PM_{10} for about three weeks in March 2002. In April 2002, another set of two TEOMs was positioned on the other side of the fan for PM_{10} measurements. The two sets of TEOMs were used for TSP and PM_{10} measurements starting May 1, 2002 for two weeks.

Effects of Filter Loading. In the week of March 26, 2002, which was after the two TEOMs had been measuring PM_{10} continuously for two weeks with new filters, one TEOM was loaded with a new filter while the other one was kept running with the two-week old, loaded filter for another week.

Comparing Different PM Concentrations. Two sets of TEOMs were used for TSP and PM_{10} measurement in May 2002, and a total of three TEOMs were used to measure TSP, PM_{10} and $PM_{2.5}$ during the week of 06/03/02.

Dust Abatement in Swine Buildings

In the CAPESH, the TEOM inlets are alternated weekly between PM_{10} and TSP (i.e. PM_{10} for one week, followed by TSP the next week). Ambient or background PM concentrations are monitored with a third TEOM located in the instrument shelter and sampling air from immediately above the shelter.

Comparing Different Sources and Treatment. The measurement points include ambient and two swine finishing barns. One swine barn (#7) is the control while the other is treated with daily sprinkling of soybean oil into the pens.

Effects of Animal Activity. In order to correlate animal activity and PM generation, animal activity is monitored with a motion detection device that generates a voltage proportional to movement. Three detectors were mounted at the ceiling of each swine barn (CAPESH study) and tilted slightly downward to sense pig activity.

Calibrations of TEOM

Variables including current and 30-min average mass concentrations ($\mu g/m^3$), total mass (μg), filter loading (%), current main and auxiliary flows (L/min), and current ambient temperature (^oC) and pressure (atm) are internally logged by the TEOM. The stored variables are downloaded through a serial cable to a PC using TEOM software. The sampling interval for these variables is programmable but the shortest interval is 10 min. The TEOM instrument has three analog output channels available for continuous data logging and can be programmed to select which of the eight variables are logged by the data acquisition system. Since the TEOM airflow is maintained at a constant volumetric flow rate, corrected for local temperature and barometric pressure, the operation of the TEOM requires that the temperature and pressure sensors be connected for proper temperature and pressure readings and flow corrections. Calibration procedures are based on routine flow auditing, leak checking, and mass calibration verification. All quality assurance procedures are coordinated with routine maintenance procedures to minimize down time.

Flow Audit. Both the sample flow rate and total flow rate are checked using a flow audit adapter with a capped nut for closing the flow splitter bypass line ports. It is recommended that the volumetric flow rates be within ±7% of the set points. The U.S. EPA requires a tolerance of ±10% for the total flow through the PM_{10} inlet. If measured flows differ by more than the stated tolerances, all settings are rechecked, and the test is performed again. Large errors in the flow may indicate other sources of error, such as a malfunctioning flow controller, a system leak, or improper temperature and pressure settings.

Leak Check. The leak check procedures are included in the operating manual (Section 7.6). The leak check are performed with NO sample filter attached to the mass transducer, which will prevent accidental damage from occurring to the sample filter cartridge when exposed to the high pressure drop (vacuum) in the sample line that the leak check creates. Flow rates should indicate less than 0.15 L/min for the main flow and less than 0.65 L/min for the auxiliary flow with the end of the sample line closed. If the flow rates are higher than these values, the plumbing is systematically checked for leaks.

Mass Calibration Verification. Since the mass transducer is permanently calibrated it never requires recalibration under normal use. However, the mass measurement accuracy of the instrument may be verified using a mass calibration verification kit.

TEOM Maintenance

The lifetime of a TEOM filter cartridge depends on the nature and concentration of the particulate sampled, and the main flow rate setting (1, 2, or 3 L/min). The filter must be exchanged when the filter loading value approaches 100%. At a flow rate of 3 L/min, 100% filter loading generally corresponds to a total mass accumulation of approximately 3 to 5 mg of particulates. Filter lifetime at a main flow rate of 3 L/min is generally 21 days at an average PM_{10} concentration of 50 $\mu g/m^3$. Flow splitter adapters for 1 and 2 L/min operation are available for use in areas with higher particulate concentrations. The typical lifetime of TEOM filter cartridges used in the APECAB and CAPESH projects ranges from 1 to 4 (?) weeks.

We have modified the the factory recommended schedule of periodic maintenance and adopted the schedule for use in livestock buildings is summarized in Table 1.

The PM_{10} inlet requires regular maintenance in livestock buildings. A wire-mesh external screen was designed for the PM_{10} inlet to remove very large particles, e.g. feathers, hair, fly parts, etc. This external screen requires cleaning every two to three days, depending on PM concentration in the air. Cleaning is accomplished by carefully removing the external screen, and, in an area downwind of the inlet unit, brushing it or cleaning with water and letting dry. After all visible dust has been removed from the external screen, it is carefully replace it on the PM_{10} head, so as not to disturb the sensor unit. The PM_{10} inlet itself is cleaned weekly.

QUALITY ASSURANCE AND QUALITY CONTROL

Quality Objectives and Criteria Principles

There are two primary data quality objectives. The first is to obtain data of sufficient quality to make applicability and compliance determinations with respect to emissions of certain regulated substances. The second is to obtain data of sufficient quality to evaluate the treatment efficiency of a technology designed to reduce emissions of these (and other) substances. For both data quality objectives, data is assessed based on the following criteria: representativeness, completeness, comparability, and accuracy.

Because a primary objective of this research is to characterize baseline emissions of particulate matter, representativeness is of particular importance. Data representativeness is a measure of the degree to which data accurately and precisely represents a characteristic of a population parameter at a sampling point or for a process condition or environmental condition.[4] Recent studies have shown that seasonal variation of gas and dust concentrations and emissions in confined animal buildings are significant.[5] (Al: it would be good to insert several of references here starting the numbering from #5) In order to obtain measurement data that has sufficient representativeness and to fully understand the effect of season on air quality, measurement should cover four seasons or the entire year. To fully achieve this goal, the measurement should be at the same site and in the same building. Otherwise, the seasonal effect cannot be effectively studied due to variations of site, building structure, and waste management practices. Data representativeness is thus assured by the overall sampling design, which includes high frequency sampling, and 6- to 15-month measurement periods at two similar side-by-side barns, and use of treatment and control sites operated following the same standard operating procedures. Data is collected over a range of seasonal conditions to further assure representativeness.

Variable and multiple ventilation exhaust air streams and potential significant background concentrations at confined animal buildings present a challenge to the selection of locations for measuring particulate matter concentrations that will adequately represent the mean concentration of the total building exhaust. Data representativeness is assured by careful selection of buildings, by carefully choosing the exhaust location, and by measuring concentrations at the ventilation inlet. The allocation of the exhaust measurement point for optimal representativeness must be conducted on a site-by-site basis because of wide variations in building layouts and configurations. Measuring PM at more than one exhaust point would be advantageous at some sites but may not be cost-beneficial.

Data completeness is a measure of the amount of valid data obtained from a measurement system, expressed as a percentage of the number of valid measurements that should have been collected (i.e., measurements that were planned to be collected).[4] Data completeness is achieved by assuring that valid data obtained from the measurement system is no less than 75% of the scheduled sampling. More data is collected if this criterion has not been met, by continuing data collection until data completeness requirements are satisfied. A greater percentage does not seem reasonable with potential lightning strikes, equipment breakdowns, university schedules, farm related problems, and limited research budgets for additional makeup monitoring. Data completeness is assured by: 1) monitoring longer at only one site, thus eliminating time loss due to installation and set up, 2) using properly maintained and reliable instrumentation, 3) maintaining a ready supply of spare parts, 4) utilizing electrical backups such as uninterruptible power supplies, 5) regular calibration procedures, 6) frequent remote access to the DAQ computer via the internet, and 7) producer collaboration and cooperation.

Data comparability is maintained by: 1) employing similar analytical methods and sampling protocol used in recent and concurrent emission studies in confined livestock and poultry facilities, 2) comparison of measurements with previous emissions rate estimates reported for swine and poultry buildings, and 3) employing well-trained personnel to collect data.

Quality Control Measures

Several specific quality control procedures are being implemented in the APECAB and CAPESH studies. The TEOM PM_{10} monitors are compared with federal reference method PM_{10} and TSP samplers operated alongside. This is being done twice, once in summer and once in winter, with the objective of obtaining a consistent relationship between the two methods.

On-line results of the three selected variables for analog output from the TEOM are displayed on a PC monitor and published to the web where continuous internet connection is possible. Research personnel check the on-line display at least daily by either remote or on-site access. Logged data files in the PC in the previous day are checked the next business day to find and correct problems. An uninterruptible power supply with battery backup is being used to prevent damage to sensitive equipment and data loss in case of power failure. High quality surge suppressors are used to protect the PC and the instruments. Performance audit samples are normally used to evaluate accuracy of field measurements. Audit samples of PM are not possible. However, a mass verification is possible to assure that the micro scale is accurate. A preweighed filter is weighed on the micro scale of each TEOM. Corrective action is taken if the weight differs by more than 2.5% from the actual filter weight. The filter weighing microbalance of the TEOM is calibrated with a NIST-traceable preweighed filter prior to the study, every 3 months, and after the study is completed. TEOM airflows are calibrated using precision airflow calibrators (Gilian Airflow Calibrators for 0.02-6.0 L/min and 2-30 L/min flow rates). Calibration records of gas analyzers, PM_{10} monitors, temperature sensors, and pressure transmitters are maintained in accordance with applicable standard operating procedures. A supply of spare parts in working condition is maintained whenever possible in order to ensure continuous data collection.

The design and operation of the instrument shelter is very important to assuring proper function of the analyzers. Instrument racks are constructed of steel, able to accept sliding trays or rails, and open to allow free air circulation for temperature control. The shelter is checked weakly for maintenance needs, e.g. replace HVAC filters, inspect for damage, etc. Proper grounding and adequate capacity of the electric power is essential for proper operation of the data acquisition.

PRELIMINARY DATA FROM SWINE AND POULTRY BUILDINGS

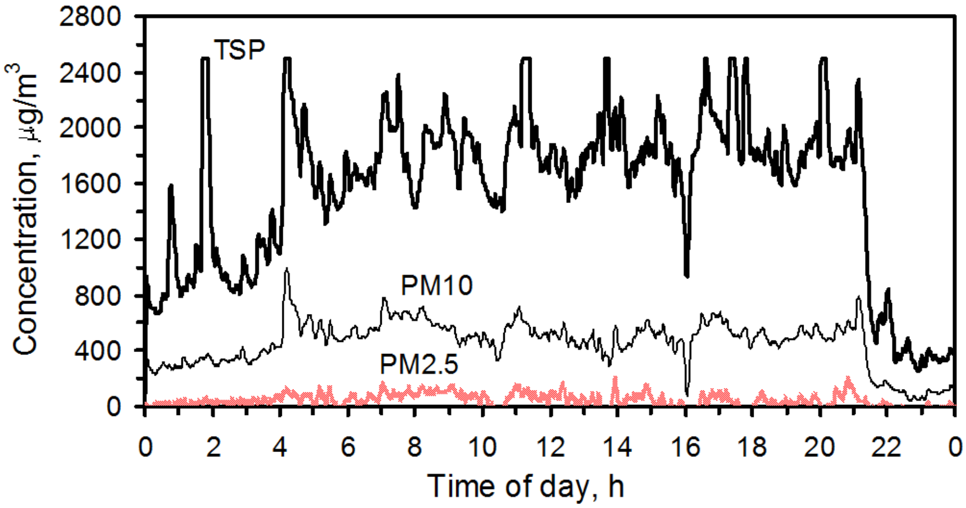
Effects of TEOM Filter Loading. On-site tests were conducted to determine the effects of TEOM filter loading on the measured concentrations. The filters of the two collocated TEOMs were heavily loaded by March 25, 2002 (after two weeks), approximately 77% according to the pressure-based indication by the TEOM. The filter was replaced in one TEOM on March 25 so that a comparison test could be conducted comparing new and loaded filters. With the new filter indicating a loading of 25% for the new filter as compared with 77% for the old filter, the 24-hr records for both TEOMs are plotted in Figure 4. The TEOMs exhibit sinusoidal patterns throughout the day with both TEOMs rising and falling in synchronous fashion. The rising and falling of the TEOM mass concentration signals are simultaneous with the rising and falling of relative humidity in the building (not shown in Figure 4), All: would it be possible to draw relative humidity on Figure 4? Thus, it is concluded that moisture is adsorbing and desorbing from the filter. When the relative humidity increases, adsorption occurs resulting in a rise in concentration. The reverse is true for desorption. However, the amplitude of pattern for the TEOM with the old filter is much greater than the TEOM with the new filter. This occurs because there are more adsorption and desorption capacity available in the loaded filter. In the case where filters were replaced simultaneously, the differences in measured concentrations were much smaller.

Comparison of PM_{10} Concentrations Measured with Collocated TEOMs. The means of the two collocated TEOM PM_{10} monitors on March 12 were 529 and 538 μg/m^3, respectively (Figure 5). The standard deviation of the differences between hourly means was 32.7 μg/m^3 or 6.1% of the mean. The concentrations measured by two collocated TEOMs were statistically similar based on an ANOVA of the hourly means ($P>0.05$). Large diurnal variations occurred as the PM_{10} mean concentration was 2.4 times higher when the lights were on as compared with the PM_{10} concentration when the lights were off. The laying hens typically participate in anticipatory feeding a few minutes before the lights go out. This phenomenon resulted in a peak of PM concentration at about 21:00 (Figures 4-5). Another reoccurring peak occurred every day when the lights were turned back on in the morning at 04:00. The means of four collocated TEOM PM_{10} monitors on April 12 were 558, 658, 716 and 768 μg/m^3, respectively (Figure 6). The standard deviation of the differences between hourly means of pairwise samplers ranged 33 μg/m^3 for TEOMs C and D to 96 μg/m^3 for TEOMs B and D. The concentrations measured by four collocated TEOMs were similar based on an ANOVA of the hourly means ($P>0.05$). Large diurnal variations occurred again as the PM_{10} mean concentration was 2.3 times higher when the lights were on as compared with the PM_{10} concentration when the lights were off.

Comparison of TSP and PM_{10} Concentrations Measured with Collocated TEOMs. The means of the two collocated TEOM TSP monitors on May 2 were 1251 and 1357 μg/m^3, respectively (Figure 7). The standard deviation of the differences between hourly means was 80 μg/m^3 or 6.1% of the mean. The TEOMs were similar based on an ANOVA of the hourly means ($P>0.05$). Large diurnal variations occurred as the TSP mean concentration was 1.7 times higher when the lights were on as compared with the TSP concentration when the lights were off. The mean PM_{10} concentration on May 2, 2002 was 542 μg/m^3 or 41% of the mean TSP concentration of 1311 μg/m^3 (Figure 7). This result is consistent with the assumption that the median mass diameter for particulate matter in swine housing is greater than 10 μm.

Comparison of TSP, $PM_{10}$and $PM_{2.5}$ Concentrations Measured with Collocated TEOMs. The mean PM_{10} concentration on June 4, 2002 was 457 μg/m^3 or 29% of the mean TSP concentration of 1,569 μg/m^3 (Figure 8). The mean $PM_{2.5}$ concentration on June 4, 2002 was 33 μg/m^3 or 2% of the mean TSP concentration (Figure 8). The mean $PM_{2.5}$, PM_{10} and TSP concentrations were 2.3, 1.8 and 1.8 times higher when the lights were on as compared with the concentrations when lights were off, respectively. Thus, it is important to measure emissions on a 24-h basis when assessing total emissions from these facilities.

Figure 8. Minute means of TSP, PM_{10}, and $PM_{2.5}$ concentration in a laying hen house on June 4, 2002.



The mean TSP concentration measured on November 8, 2002 in the swine buildings were 1,143 and 375 μg/m^3 in the untreated barn A and treated barn B, respectively (Figure 9). The reduction due to oil sprinkling was 67% ($P<0.05$). Large fluctuations occurred due to heavily loaded filter in the barn A TEOM (>60% indication). The mean ambient concentration was only 25 μg/m^3 or 7% of that in the treated building.

Figure 9. Comparison of control (Barn A), treated, and ambient TSP concentration, 11/08/02.

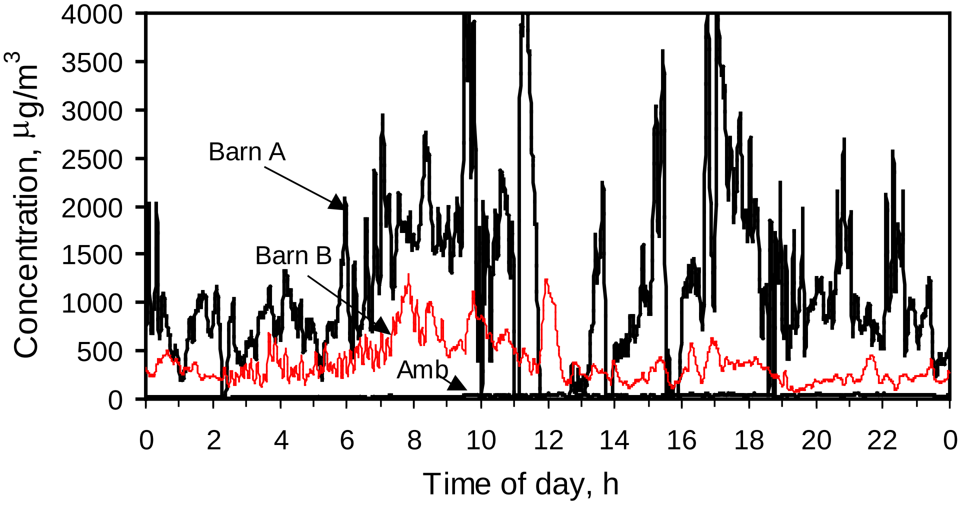
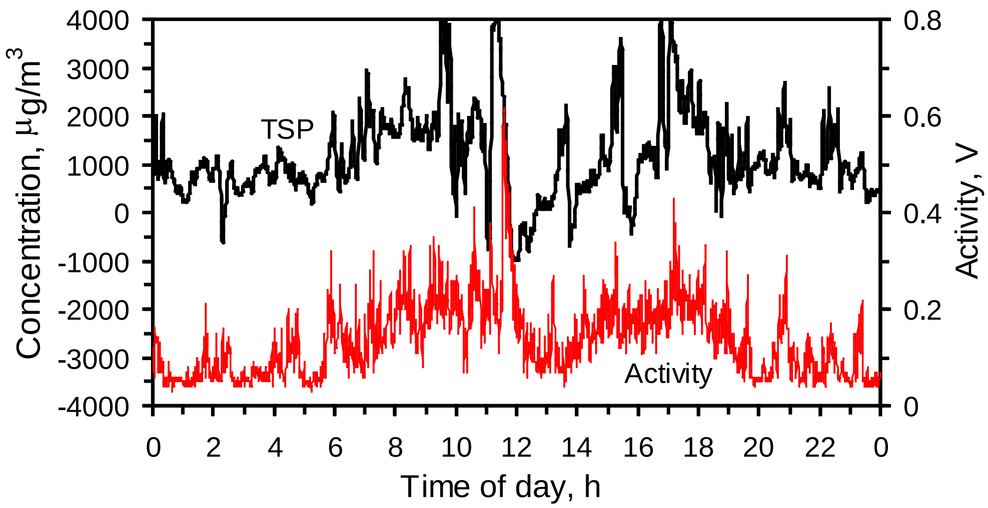


Figure 10 shows the correlation between TSP and animal activity as recorded by one sensor in barn A. The correlation coefficient between the minute means of the two variables was 0.43.

Figure 10. Effects of animal activity on TSP concentration, minute mean of 11/08/02.



CONCLUSIONS

The following conclusions stem from this study:

1. More frequent maintenance of the TEOM is necessary when used to measure PM concentrations in swine and poultry buildings as compared with ambient measurements.
2. External screens were necessary to prevent rapid plugging of the bug screen in the inlet head.
3. Minute means of mass concentrations exhibited a sinusoidal pattern that followed that of relative humidity indicating that the mass concentration measurements were affected by condensation and evaporation of moisture from the filter.
4. Filter loading increased the humidity effect, probably due to increased adsorption capacities for water vapor.
5. Collocated TEOMs with TSP and PM_{10} agreed well when placed near the inlet of exhaust fans in a laying hen house.
6. The average daily mean TSP concentration (n=2) at the laying hen house was 1440 $\mu g/m^3$.
7. The average daily mean PM_{10} concentration (n=4) at the laying hen house was 552 $\mu g/m^3$.
8. The daily mean $PM_{2.5}$ concentration (n=1) at the laying hen house was 33 $\mu g/m^3$.
9. The daily mean TSP concentration (n=1) at an untreated swine house was 1143 $\mu g/m^3$ and was 67% less in a swine house sprinkled with soybean oil.
10. The daily mean ambient TSP concentration (n=1) between the swine house was 25 $\mu g/m^3$.
11. Concentrations of PM in swine houses was confirmed to be well correlated with animal activity as recorded by a motion detector.

ACKNOWLEDGMENTS

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ABBREVIATIONS

APECAB	Aerial Pollutant Emissions from Confined Animal Buildings
CAPESH	Control of Air Pollutant Emissions from Swine Housing
IFAFS	Initiative for Future Agricultural and Food Systems

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TABLES

Table 1. Maintenance schedule for the TEOM.

Maintenance item	**Factory**	**Livestock Buildings**
Clean external screen	-	As necessary
Clean PM-10 inlet	Upon filter exchange	Weekly
Exchange in-line filters	6 months or when loaded	When loaded
Clean air inlet system	6 months	3 months or as necessary
Leak test	Annually	Bimonthly
Mass flow controller calibration	Annually	Bimonthly
Analog board calibration	Annually	6 months
Mass calibration verification	Annually	Bimonthly

FIGURES

Figure 1. Flow schematic for the TEOM.

Figure 2. Schematic of monitoring plan at finishing barn, DAQ = data acquisition, PREF = primary representative exhaust fan.

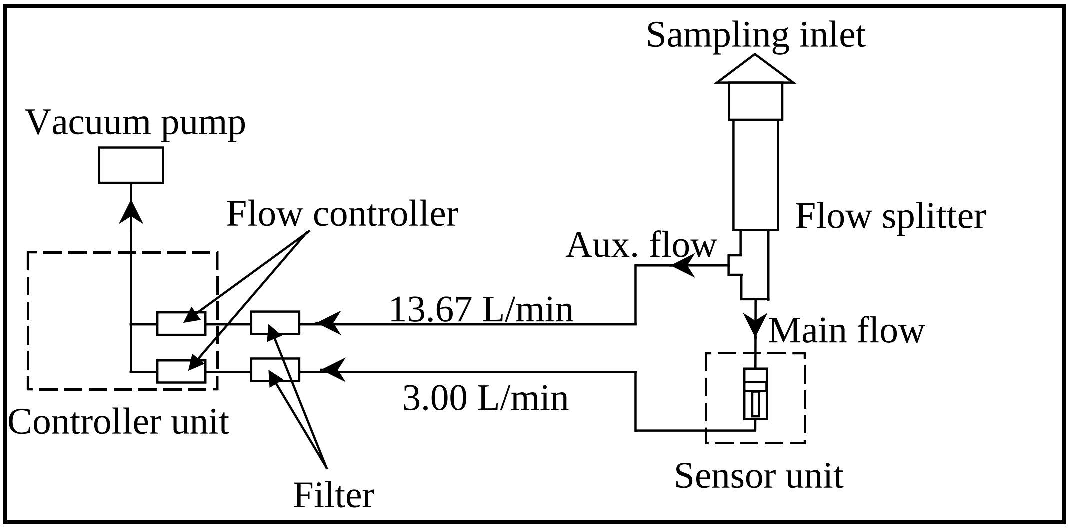
Figure 3. Dust measurement devices in laying hen house: Collocated TEOMs with PM_{10} inlet (A), Wedding total mass for the TSP range (B), and Wedding PM_{10} (C).

Figure 4. Effects of filter loading: PM_{10} concentration of 1- and 15-day old filters, 03/26/02.

Figure 5. Minute means of PM_{10} concentrations measured with two collocated TEOMs with new filters (3/12/02).

Figure 6. Minute means of PM_{10} concentration measured with 2-day old filters using four collocated TEOMs (04/03/02).

Figure 7. Minute means of TSP and PM_{10} concentrations in laying hen house, 05/02/02.



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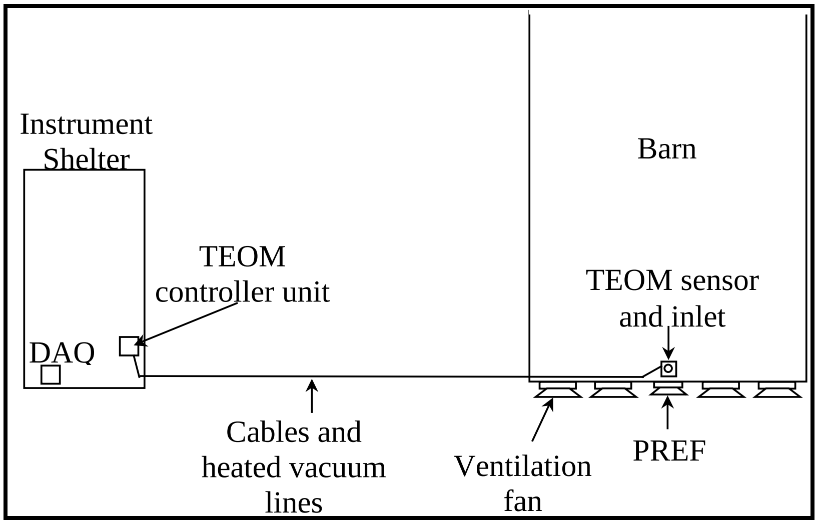

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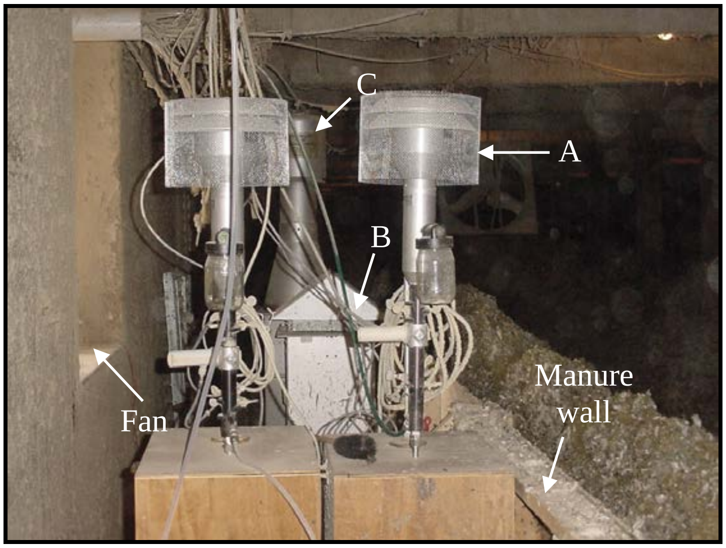

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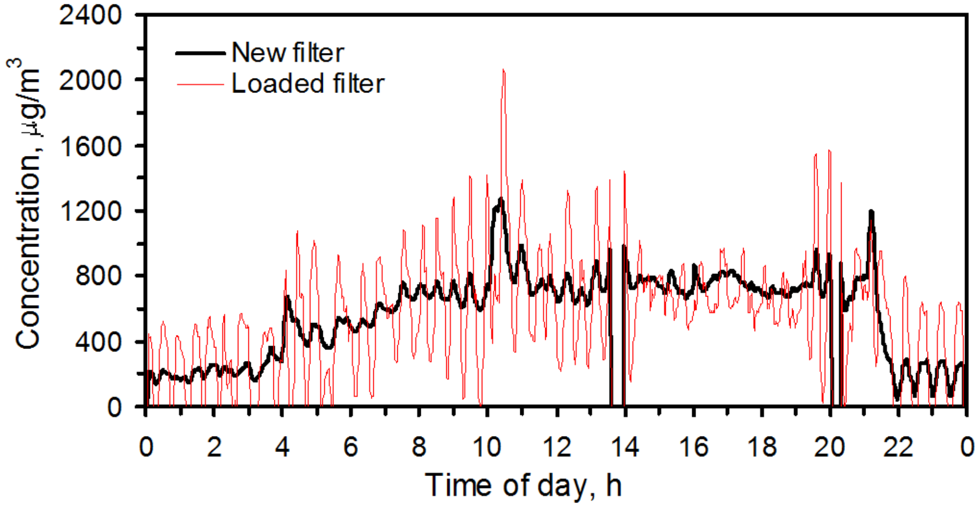

Figure 4. Effects of filter loading: PM_{10} concentration of 1- and 15-day old filters, 03/26/02.

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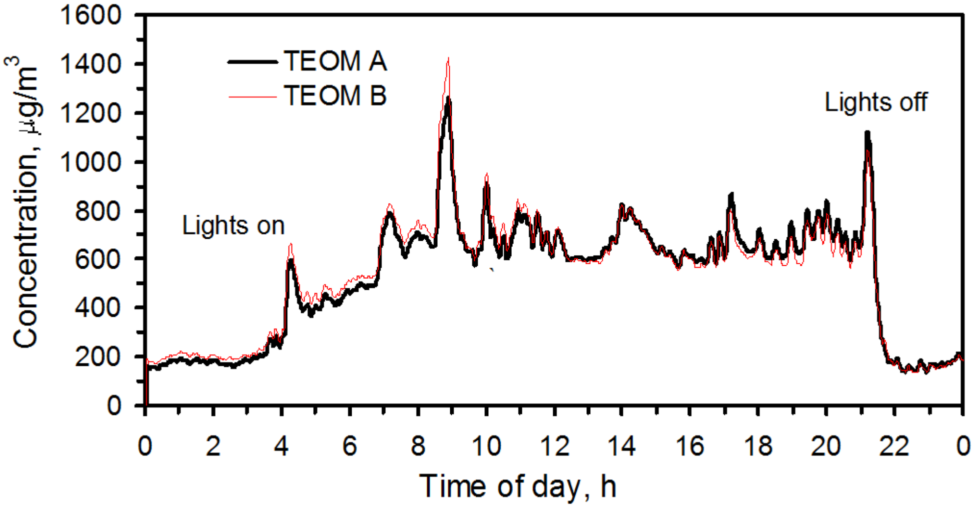

Figure 5. Minute means of two collocated TEOMs with new filters: PM_{10} concentration, 3/12/02.

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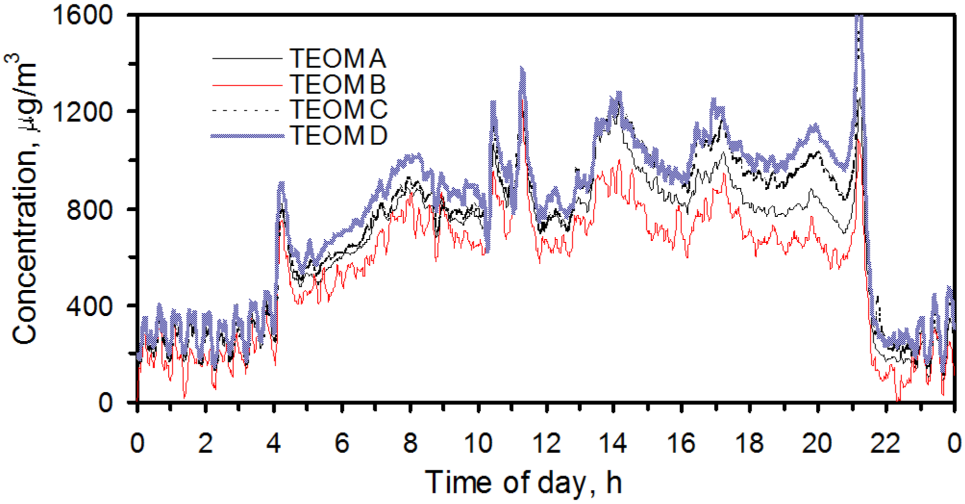

Figure 6. Minute means of four collocated TEOMs: PM_{10} concentration with 2-day old filters, 04/03/02.

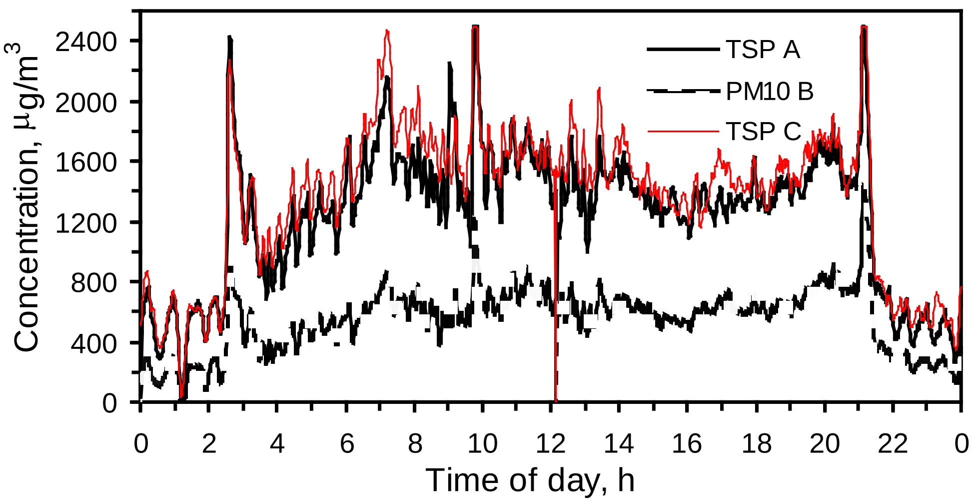

Figure 7. Minute means of TSP and PM_{10} concentrations in laying hen house, 05/02/02.