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Comparison of Measured Total Suspended Particulate Matter Concentrations Using Tapered Element Oscillating Microbalance and a Total Suspended Particulate Sampler

Sheryll B. Jerez, Yuanhui Zhang, and Joshua W. McClure
Department of Agricultural and Biological Engineering, University of Illinois, Urbana, IL

Larry Jacobson
Department of Biosystems and Agricultural Engineering, University of Minnesota, St. Paul, MN

Albert Heber
Department of Agricultural and Biological Engineering, Purdue University, West Lafayette, IN

Steven Hoff and Jacek Koziel
Agricultural and Biosystems Engineering, Iowa State University, Ames IA

David Beasley
Biological and Agricultural Engineering, North Carolina State University, Raleigh, NC

ABSTRACT

A comparison of the concentration of the total suspended particulate (TSP) matter measured by the tapered element oscillating microbalance (TEOM) monitor and the isokinetic TSP samplers developed at the University of Illinois was carried out in several types of confinement livestock buildings. In a majority of the measurements done, the dust concentration measured by the TEOM monitor was lower than the University of Illinois at Urbana-Champaign (UIUC) isokinetic TSP sampler; the TEOM monitor tended to underestimate the total dust concentration by as much as 54%. The difference in measurements can be attributed to the sampling efficiency of the TEOM monitor sampling head and the loss of some semivolatile compounds and particle-bound water because of heating of the TEOM monitor sampling stream to 50 °C. Although several articles in the literature supported the latter argument, this study did not investigate the effect of heating the sampling stream or the effect of moisture on the relative difference in dust concentration measurements. The model that best describes the relationship between the two methods was site specific, that is, the linear regression model was applicable only to four of the sites monitored. The measured total dust concentration in livestock buildings range from ~300 to 4000 μg/m^3; a higher correlation coefficient between TEOM-TSP and UIUC-TSP monitors was obtained in swine facilities than those obtained in a laying facility.

IMPLICATIONS

The use of TEOM monitors in livestock building applications is gaining popularity because of the need for continuous monitoring of particulate matter emission. Results of the comparison between the TEOM monitor and the manual filter-based mass measurement method showed that TEOM monitor measurements were generally lower than those of the manual method by as much as 54%. Thus, although the TEOM monitor can provide continuous real-time data, the manual method is still more reliable and accurate. This finding is significant, because it implies that adjustments of operating parameters of the TEOM monitor to obtain better agreement with the manual method are necessary before it can be used in livestock applications.

INTRODUCTION

Particulate matter (PM) measurement in confined animal facilities in many ways was more complicated than for a gaseous pollutant. In the United States, U.S. Environmental Protection Agency (EPA) standards for determination of particulate emissions from stationary sources are designed for in-stack or duct sampling and require sampling at a location a number of duct diameters away from a known disturbance. Mechanically ventilated livestock buildings do not have stacks nor extended ducts downstream and upstream of the fans and have various designs; some buildings have ventilation fans installed on the sidewalls; others are tunnel ventilated, in which the ventilation fans are located at one end of the building and the air enters the opposite end or at the sidewalls. EPA Method 5[1] requires isokinetic sampling conditions to ensure that a representative sample is extracted from the duct or stack; Method 1 requires that portions of the sample be extracted from a number of different locations in the duct cross section, and at each of these locations, isokinetic sampling is also required.

The researchers at University of Illinois at Urbana-Champaign (UIUC) had developed a total suspended PM

(TSP) sampling system to measure PM dust concentration in mechanically ventilated livestock buildings.[2] This device is not a reference method for TSP measurement; however, it allows isokinetic measurement of dust concentration at three sampling locations across the duct cross section of exhaust fans in livestock buildings, and the sampling nozzles can be located at a number of duct diameters away from the fan depending on the prevailing air velocity. It has an interchangeable inlet and a critical orifice that controls the flow rate at 0.02 m^3/min. Particles are drawn through the inlet and collected on a glass fiber filter. The particle concentration is calculated by measuring the weight gain of the filter. It is an inexpensive and a versatile measurement device, but it does not provide continuous and real-time particulate concentration data.

Tapered element oscillating microbalance (TEOM) is an automatic and near-real-time particulate sampler. It is designated by EPA as an automated equivalent method for the determination of ambient concentrations of PM measured as coarse PM (PM_{10}; EPA Designation No. EQPM-1090-079) and is a widely used method for direct measurement of particle concentrations in ambient air sampling conditions.[3–7] When the TEOM monitor is fitted with a TSP inlet, its performance matches that of the EPA reference method on TSP measurement using a high-volume TSP sampler[8] very closely.[9] The use of TEOM monitors in livestock building applications for the determination of pollutant emission rates has been explored recently.[10,11]

Previous studies on the use of a TEOM monitor in livestock building applications have focused on direct application of the TEOM monitor on continuous dust concentration measurements to determine particulate emissions; no comparison was made on its performance with respect to other gravimetric methods of dust concentration measurements. The objective of the current study was to compare the measured dust concentration using both the TEOM monitor and the UIUC-TSP samplers. This work is part of the Aerial Pollutant Emissions from Confined Animal Buildings project in six states: Illinois, Indiana, Iowa, Minnesota, North Carolina, and Texas. Because of limited availability of data from North Carolina, results that were presented were those of Illinois, Indiana, Iowa, Texas, and Minnesota. A majority of the discussions were derived from measurements done in a swine facility in Illinois.

EXPERIMENTAL WORK

Description of the Measurement Sites

Particulate concentration measurements using TEOM monitor and UIUC-TSP samplers were conducted in six states: Illinois, Indiana, Iowa, Minnesota, North Carolina, and Texas; however, results that were presented were those of Illinois, Indiana, Iowa, Minnesota, and Texas because of limited data available in North Carolina. Four swine houses (farrowing house in Illinois, breeding/gestation facility in Minnesota, and finishing houses in Iowa and Texas) and two chicken facilities (layer and broiler houses in Indiana and North Carolina, respectively) were monitored, and measurements were conducted from two mechanically ventilated barns from each site. The animal inventory in each barn consisted of 250,000 layers in Indiana and 630, 56, 960, and 1080 swine in Minnesota, Illinois, Iowa, and Texas, respectively. The chicken layer building in Indiana had a high-rise manure system; deep pit manure storage was used in the swine finishing barns in Iowa, whereas the barns in Minnesota, Illinois, and Texas all had a pull-plug manure system.

The ambient temperature and relative humidity (RH) in all of the sampling sites during the sampling period varied greatly. The ambient temperature ranged from −25 to 27 °C, whereas the RH ranged from 26% to 100%. The indoor and exhaust air condition, however, did not vary significantly among the sites. The indoor air temperature in swine buildings ranged from 17 to 29 °C, whereas the exhaust air temperature and RH was from 10 to 30 °C and from 32% to 80%, respectively. In the layering chicken barns, the indoor and exhaust air temperatures ranged from 21 and 29 °C and from 17 to 25 °C, respectively; the exhaust RH was between 45% and 76%.

Description of the Measured Parameters

The concentration of the TSP was monitored along with the building ventilation rate, indoor temperature, exhaust air temperature, and RH. The building ventilation rate was monitored for emission rate calculation of gases and PM, including TSP; the scope of discussion in this paper, however, is limited to the measured particulate concentration. Indoor and exhaust air temperatures were measured using copper-constantan thermocouples (type T) connected to a 16-bit thermocouple module (FC-TC-120, National Instruments, Austin, TX). An electronic RH/temperature transmitter (Model HMW61, Vaisala, Woburn, MA) housed in a NEMA 4 enclosure monitored the temperature and RH at the exhaust.

The concentration of TSP was measured using a TEOM monitor (Series 1400a, Rupprecht and Patashnick Co., Inc., Albany, NY) fitted with a TSP inlet (Part Number 10−002929, Rupprecht and Patashnick Co., Inc., Albany, NY), hereafter referred to as TEOM-TSP and UIUC-TSP samplers operated side-by-side and simultaneously. The samplers that were used in each facility were the same for all of the sampling events. The TEOM-TSP inlet is designed to sample a 100-μm diameter particle in still air, and the suction velocity into the TSP is simply equal to the terminal velocity of a 100-μm diameter unit density sphere, which is 25 cm/sec at 20 °C. The UIUC-TSP sampler is designed for isokinetic sampling of TSP and had a near-unity sampling efficiency for all of the particle sizes in the sampled air.

The TEOM monitor and UIUC-TSP samplers were located immediately upstream of the primary fan in each barn. Because of limited space in all of the barns monitored, both samplers were positioned ≤10 m apart. TSP concentrations were measured periodically from September to December 2003 for Illinois, September 2003 for Indiana, January to March 2004 for Iowa, August 2003 to January 2004 for Minnesota, and November 2003 to January 2004 for Texas. In Illinois and Minnesota, 16 sampling events were completed; each sampling event lasted ≥46 hr for Illinois and 24 hr for Minnesota to obtain enough PM (>3 mg, EPA Method 5i). Six collocated measurements were done in Indiana with each measurement

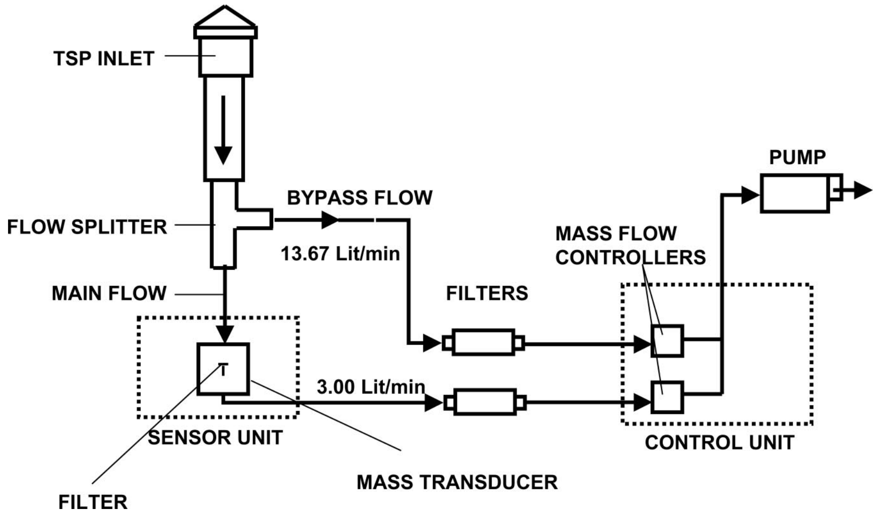

Figure 1. Flow schematic and major components of a TEOM sampler fitted with a TSP inlet.

lasting ≥21 hr. Iowa had 35, whereas Texas had 17 collocated sampling data, with a sampling period of ≥24 hr. Sampling duration and frequency were dictated by dust loading and activities in the barns.

Description of the Samplers

TEOM. The TEOM monitor is a real-time device for mass concentration measurements of TSP, PM_{10}, and fine PM ($PM_{2.5}$) by using the appropriate type of inlet. In this study, the TEOM monitor[12] was fitted with a TSP sampling head operated at its design flow rate of 16.67 L/min. The TSP inlet used in the TEOM monitor was not designed for isokinetic sampling in ambient air; rather, it was designed to be able to sample 100-μm particles in still air, and the suction velocity is simply equal to the terminal velocity of a 100-μm diameter unit density sphere, which is 25 cm/sec at standard atmospheric conditions. The TEOM-TSP consists of the inlet and sensor and control units (Figure 1). Particle-laden gas streams enter the inlet and are continuously drawn through a filter mounted on the tip of an oscillating tapered element.[12] The tapered element is a hollow cantilever beam, with one end free to vibrate and the other (wider) end fixed. The collection of particles by the filter changes the natural frequency of oscillation. Eq 1 describes the basis for mass concentration measurement by the TEOM.[13] As the mass of particles deposited on the filter, Δm, increases, the change between the frequencies after (f_a) and before (f_b) sample collection decreases—the change in aerosol mass on the filter is determined by measuring only this change in frequency; K_o is a constant unique to a tapered element. A microprocessor converts the oscillation frequency to mass and then to mass concentration every 2 seconds.

$$\Delta m = K_o\left(\frac{1}{f_b^2} - \frac{1}{f_a^2}\right) \qquad (1)$$

The flow rate through the analyzer is controlled using thermal mass flow controllers; air at 16.67 L/min is divided between the filter flow (3 L/min) and the auxiliary flow (13.67 L/min). The sampling stream is heated at 50 °C to avoid changes in the microbalance response because of temperature fluctuations, as well as to prevent water vapor condensation. Patashnick and Rupprecht[11] provided other detailed information on the TEOM monitor.

TEOM-TSP was located upstream of and ≥0.5 m away from the primary exhaust fan to minimize any disturbance with the airflow going into its inlet; the prevailing velocity in its location was <2 m/sec. It was operated simultaneously with the UIUC-TSP system, whenever possible, and data was collected every 60 sec throughout the sampling period.

UIUC-TSP Sampler. The UIUC-TSP system consisted of an isokinetic sampling head attached to a 37-mm open-faced filter holder, a critical venturi, and a sampling pump (Figure 2). The sampling head was replaceable, that is, different size of sampling heads can be used depending on the prevailing airflow velocity in the area; a sampling head with an entrance diameter of 14.6 mm for a 2-m/sec sampling velocity was used. The nozzle was stainless steel with a 15 ° tapered edge and a cone angle of 6°; these meet the EPA nozzle design specifications in Method 201A.[1] The rear of the sampling head was designed to fit into a 37-mm plastic filter holder. The critical venturi downstream of the filter controls the flow rate through the sampling head at a constant rate of 0.02 m^3/min as long as the upstream pressure is maintained above the critical pressure of 10 kPa.[14] Three sets of sampling head assemblies were connected to a sampling pump allowing dust concentration to be measured at three locations across the cross section of the exhaust fan; one nozzle was located in the middle section of the fan cross section, and the other two were positioned near the top and bottom outer edges of the fan. Details of the design are available in McClure et al.[2]

Isokinetic sampling is achieved by positioning the nozzles upstream of the primary exhaust fan facing the airflow at locations with an average airflow velocity of 2 m/sec ± 10%. The particles were collected on the glass fiber filter mounted on the open-faced filter holder. The

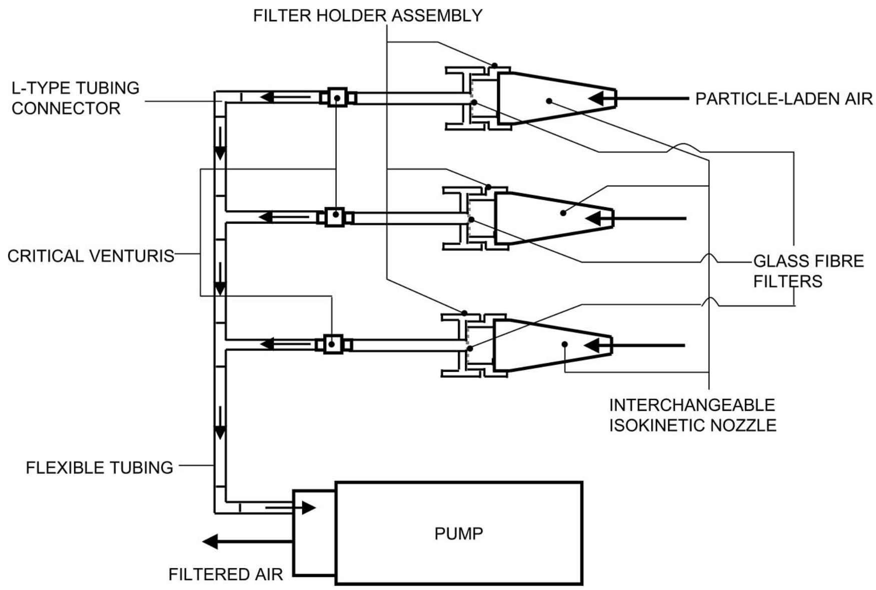

Figure 2. Flow schematic and components of the UIUC-TSP isokinetic sampler.

filters were equilibrated in constant humidity chambers before and after sampling for at least 24 hr and weighed using a balance with a resolution of 0.01 mg. Sampling duration in each TSP measurement was flexible, varying from 21 to 123 hr, depending on the conditions inside the barn.

Data Analysis

Calculation of Particle Concentration. For UIUC-TSP, the amount of dust collected on the filter was the difference between the weight of the loaded filter and its clean weight before sampling; particle concentration is the mass of dust collected divided by the volume of sampled air. To take into account the potential dust loading bias because of possible leakage in the filter holder, field blanks (filters enclosed in filter holders that were exposed to all aspects of sampling except collection) were used in some of the test runs; the amount of dust collected on these blanks was negligible (<2% of the collected mass) and was not used in the analysis. The average particle concentration measured from the three sampling locations across the duct cross section was calculated and compared with the particle concentration measured by the TEOM-TSP monitor. The recorded particle concentration by the TEOM-TSP monitor was averaged over the sampling period approximately matching the sampling period of the UIUC-TSP sampler to allow direct comparison of the two methods of measurements.

Statistical Analysis. The average concentrations for the TEOM-TSP monitor were calculated as the arithmetic mean of the 60-sec readings over the sampling period; the average particle concentration for the UIUC-TSP was the arithmetic mean of the measurements from the three samplers that were used simultaneously. The standard deviations of the measured concentrations were also calculated: for TEOM-TSP, it was the variation among the measured 60-sec readings, whereas for UIUC-TSP, it was calculated from the three measured concentrations. The relationship between TEOM-TSP and UIUC-TSP samplers was investigated by linear regression analysis using SAS for Windows v8.02.

RESULTS AND DISCUSSIONS

The average hourly data collected from the TEOM-TSP monitor was used to determine the hourly and day-to-day variation in dust concentration. Figure 3 shows typical variations in dust concentration measured in a swine farrowing facility in Illinois for two sampling days in October. It shows clear diurnal peaks from 7:00 a.m. to 8:00 a.m. and at 9:00 p.m. Because specific activities in the barn (e.g., feeding, animal activity, and worker activity) were not recorded, the causes of the peaks in the early morning and late at night are not known. The peak in the early morning hours, however, may be attributed to the operation of the feed conveyors. The hourly and daily variations in dust concentration, because of different levels of activities inside the barn, explain the high standard deviation for TEOM-TSP monitor measurements presented in Tables 1 and 2. The UIUC-TSP sampler does not provide an hourly dust concentration that can be used for comparison.

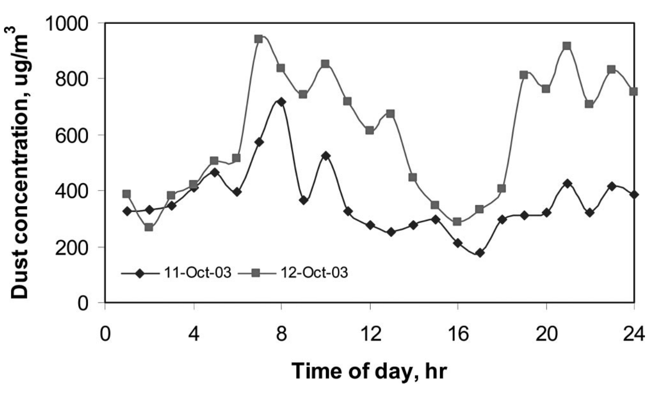

Figure 3. Hourly variation in dust concentration in a swine farrowing building in Illinois measured using a TEOM-TSP monitor.

Table 1. Temperature, RH, and dust concentrations measured in a swine farrowing house in Illinois between September and December 2003.

Date (2003)	Temperature (± SD), °C	RH (± SD) %	Average Dust Concentration (± SD), μg/m³		TEOM-TSP/ UIUC-TSP Ratio
			UIUC-TSP	TEOM-TSP	
Sep 26	23 (± 0.9)	50.0 (± 9.1)	1134 (± 40)	1008 (± 348)	0.89
Sep 29	22 (± 1.3)	49.5 (± 8.0)	1384 (± 85)	1040 (± 278)	0.75
Oct 1	22 (± 1.3)	49.5 (± 8.0)	1590 (± 148)	1207 (± 310)	0.76
Oct 3	21 (± 1.8)	50.7 (± 7.5)	329 (± 9.0)	249 (± 142)	0.76
Oct 10	24 (± 1.5)	53.8 (± 10.7)	637 (± 159)	518 (± 300)	0.81
Oct 13	22 (± 1.3)	49.0 (± 9.8)	962 (± 548)	518 (± 225)	0.54
Oct 15	23 (± 0.7)	49.0 (± 6.4)	1306 (± 120)	905 (± 331)	0.69
Oct 20	23 (± 1.7)	51.3 (± 9.9)	1668 (± 199)	870 (± 365)	0.52
Oct 22	22 (± 1.3)	52.7 (± 9.7)	1247 (± 109)	997 (± 362)	0.80
Oct 27	22 (± 0.7)	51.5 (± 4.6)	680 (± 28)	531 (± 210)	0.78
Oct 30	[a]	[a]	363 (± 9)	309 (± 160)	0.85
Nov 3	[a]	[a]	671 (± 37)	508 (± 260)	0.76
Nov 5	[a]	[a]	985 (± 102)	809 (± 326)	0.82
Nov 19	22.9 (± 0.9)	50.7 (± 5.7)	613 (± 420)	459 (± 223)	0.75
Nov 26	21.5 (± 0.3)	49.4 (± 4.3)	1412 (± 152)	999 (± 309)	0.71
Dec 12	22.0 (± 0.4)	47.8 (± 3.8)	927 (± 109)	791 (± 268)	0.85

[a]No available temperature and RH data because of malfunctioning of the data logger.

Figure 4 shows the comparison of the average dust concentration measured using TEOM-TSP and UIUC-TSP samplers in a swine facility in Illinois. It can be seen from the graph that the measurements by the two samplers are strongly correlated; occurrence of peak concentration at various times can be attributed to the number of animals, activity in the barn, and the condition of the barn, that is, at the beginning of the farrowing cycle (10/3 in the graph), there was a lesser number of animals, and the rooms were cleaner than toward the end of the cycle (10/23). The dust concentration measured in 16 sampling events from September to December ranges from 249 to 1207 μg/m³ for TEOM-TSP and from 329 to 1590 μg/m³ for UIUC-TSP (Table 1); measured field blanks range from 0% to ~2% of the total dust collected during sampling. None of the reported average dust concentrations for both samplers exceeded 2.4 mg/m³, which was the suggested threshold exposure limit for total dust concentration in swine buildings.[15] However, in all 16 of the measurements, the UIUC-TSP sampler recorded a higher mass concentration than the TEOM-TSP monitor. The calculated TEOM-TSP/UIUC-TSP ratio ranges from 0.52 to 0.89, corresponding to dust concentration percentage difference of 11–48%.

Table 2 shows the measured dust concentration for sites in Indiana, Iowa, Minnesota, and Texas. Dust concentration measured using the UIUC-TSP sampler in a laying house in Indiana ranges from ~2943 to 4011 μg/m³; dust concentration in a breeding/gestation swine facility in Minnesota ranges from 508 to 2826 μg/m³, and from 930 to 3310 μg/m³ and from 2084 to 3687 μg/m³ for the swine finishing facilities in Iowa and Texas, respectively. In all of the collocated measurements done in Indiana, Iowa, and Texas, the TEOM-TSP monitor gave consistently lower values than UIUC-TSP; the difference in dust concentration measurements for Indiana was from 30% to 54%, 2% to 74% for Iowa, and 21% to 39% for Texas. At the Minnesota site, a quarter of the dust concentration measurements using the TEOM-TSP monitor were higher than those of the UIUC-TSP measurements, whereas about half of the measurements using the TEOM-TSP monitor was ≤6% lower than those of the UIUC-TSP measurements. These results suggest that the variability of the difference in the measured dust concentrations using TEOM-TSP and UIUC-TSP samplers differs from one site to another.

Recorded differences between the TEOM monitor and other gravimetric monitors are well documented in ambient air sampling applications; these works, however, were limited to comparisons of specific size fractions. These include the work of Ayers et al.,[4] who compared $PM_{2.5}$ aerosol loading by a Rupprecht and Patashnick TEOM monitor series 1400 and two manual gravimetric samplers in measurements done in Australian cities. They found that the TEOM monitor systematically revealed lower results than the gravimetric samplers by an average of >30%. The lower results were attributed to volatilization of semivolatile aerosol components because of heating of the TEOM monitor sampling stream.

In another study, Price et al.[6] compared PM_{10} measured with a Rupprecht and Patashnick TEOM monitor series 1400 with European Union reference gravimetric method. Results showed that the two samplers correlate well at low values of PM_{10}, but as the dust concentration increases, the gravimetric method recorded higher concentration than the TEOM monitor. After comparing the results of the TEOM monitor operated at 50 °C and the TEOM monitor fitted with a drier and operated at a lower temperature, they concluded that the retention of particle-bound water by the European Union reference method might have caused the observed differences.

In this study, however, the difference in the concentration measurements by the UIUC-TSP and TEOM-TSP

Table 2. Measured dust concentrations in swine and chicken houses in Indiana, Iowa, Minnesota, and Texas using UIUC-TSP and TEOM-TSP samplers.

Site	Average Dust Concentration (± SD), μg/m³		TEOM-TSP/ UIUC-TSP Ratio
	UIUC-TSP	TEOM-TSP	
Indiana	3179 (± 55)	2225 (± 1066)	0.70
	2943 (± 190)	1538 (± 762)	0.52
	4011 (± 474)	2358 (± 1165)	0.59
	3294 (± 701)	1523 (± 885)	0.46
	3120 (± 79)	1646 (± 1080)	0.53
	3075 (± 190)	1698 (± 3257)	0.55
Iowa	1369 (± 191)	744 (± 294)	0.54
	926 (± 188)	812 (± 549)	0.88
	1838 (± 415)	904 (± 641)	0.49
	1905 (± 479)	805 (± 605)	0.42
	2220 (± 565)	608 (± 443)	0.27
	2049 (± 404)	599 (± 361)	0.29
	1860 (± 509)	665 (± 712)	0.36
	2315 (± 76)	594 (± 371)	0.26
	2554 (± 294)	881 (± 753)	0.34
	1990 (± 156)	757 (± 773)	0.38
	2011 (± 246)	808 (± 795)	0.40
	2291 (± 267)	674 (± 518)	0.29
	2255 (± 163)	804 (± 762)	0.36
	3036 (± 103)	1816 (± 1127)	0.60
	3310 (± 83)	2227 (± 1244)	0.67
	3127 (± 231)	2377 (± 1108)	0.76
	3269 (± 129)	2185 (± 1190)	0.67
	3261 (± 170)	2245 (± 1043)	0.69
	1413 (± 295)	1164 (± 528)	0.82
	1167 (± 319)	1142 (± 558)	0.98
	1285 (± 319)	1152 (± 576)	0.90
	1716 (± 438)	1190 (± 735)	0.69
	1889 (± 497)	1242 (± 718)	0.66
	1578 (± 326)	1527 (± 947)	0.97
	1742 (± 391)	1227 (± 619)	0.70
	1946 (± 382)	1309 (± 805)	0.67
	1865 (± 404)	1332 (± 869)	0.71
	2043 (± 412)	1379 (± 904)	0.67
	2175 (± 451)	1456 (± 850)	0.67
	2775 (± 447)	1917 (± 955)	0.69
	2773 (± 241)	1815 (± 875)	0.65
	2970 (± 184)	1945 (± 820)	0.65
	2636 (± 149)	1736 (± 809)	0.66
	3033 (± 167)	1973 (± 980)	0.65
	3243 (± 141)	2066 (± 975)	0.64
Minnesota	661 (± 16)	368 (± 287)	0.56
	585 (± 23)	344 (± 259)	0.59
	915 (± 68)	660 (± 368)	0.72
	725 (± 138)	373 (± 350)	0.51
	508 (± 109)	293 (± 187)	0.58
	1083 (± 147)	774 (± 554)	0.71
	1582 (± 66)	765 (± 333)	0.48
	1561 (± 47)	1460 (± 796)	0.94
	1426 (± 53)	1352 (± 822)	0.95
	1448 (± 92)	1416 (± 951)	0.98
	1326 (± 29)	1546 (± 740)	1.17
	1884 (± 86)	605 (± 271)	0.32
	2826 (± 60)	2747 (± 969)	0.97
	2363 (± 122)	2627 (± 1378)	1.11
	2108 (± 74)	2126 (± 1107)	1.01
	1706 (± 58)	1733 (± 961)	1.02

Table 2. Cont.

Site	Average Dust Concentration (± SD), μg/m³		TEOM-TSP/ UIUC-TSP Ratio
	UIUC-TSP	TEOM-TSP	
Texas	2242 (± 281)	1502 (± 595)	0.67
	2264 (± 544)	1785 (± 833)	0.79
	2084 (± 158)	1559 (± 692)	0.75
	2562 (± 201)	2024 (± 788)	0.79
	3136 (± 218)	2327 (± 864)	0.74
	3368 (± 167)	2327 (± 874)	0.69
	3257 (± 408)	2090 (± 587)	0.64
	3028 (± 218)	1941 (± 726)	0.64
	3687 (± 386)	2235 (± 827)	0.61
	2824 (± 166)	2019 (± 793)	0.71
	2217 (± 91)	1475 (± 319)	0.67
	3028 (± 127)	1987 (± 284)	0.66
	2935 (± 332)	1964 (± 482)	0.67
	3206 (± 740)	2194 (± 271)	0.68
	3177 (± 744)	1968 (± 513)	0.62
	2961 (± 811)	2045 (± 650)	0.69
	3737 (± 202)	2140 (± 566)	0.57

can be attributed, in large part, to the anisokinetic sampling condition for TEOM-TSP. Because the suction velocity of the TEOM-TSP matches the settling velocity of 100-μm particles, which is 25 cm/sec, and the prevailing air velocity around the TEOM-TSP inlet was higher than the suction velocity, a majority of the mass collected by the TEOM-TSP consisted of small particles, because large particles were lost outside the sampler. Additional discussion on the effect of anisokinetic sampling conditions on TEOM-TSP performance is presented in the next section. Future studies on the measurement of size distribution of particles emitted from confined animal buildings and side-by-side sampling of TSP and PM_{10} using TEOM monitors are being planned; results from these studies may provide quantitative measure of the amount of large particles lost during anisokinetic sampling using a TEOM monitor.

Figure 5 shows the combined measured dust concentration from all five of the sites; it can be seen from the

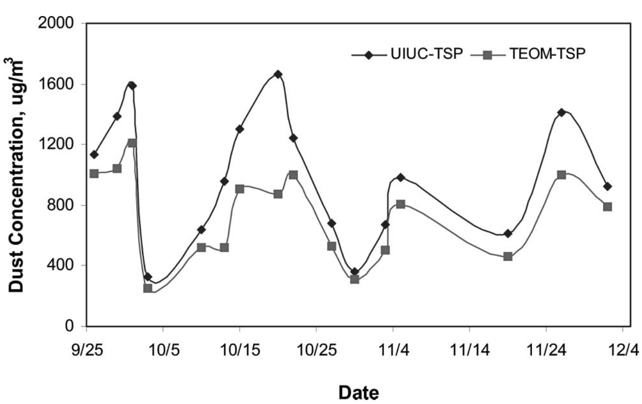

Figure 4. Measured dust concentrations in a swine farrowing house in Illinois using UIUC-TSP and TEOM-TSP samplers at 16 sampling events between September and December 2003.

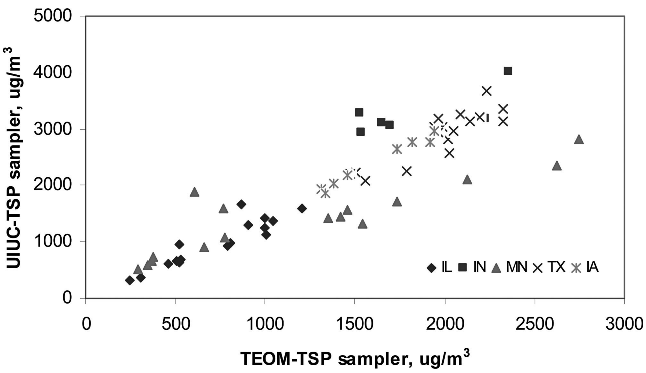

Figure 5. Relationship between the dust concentration (μg/m^3) measured using TEOM-TSP and UIUC-TSP samplers.

graph that despite the scatter of data at higher concentrations, the model that best describes the relationship between the TEOM-TSP and UIUC-TSP samplers for the measurements done in four sites is linear, with the data in Illinois showing the highest correlation, whereas data from Indiana had the lowest correlation (Table 3); for Iowa, linear regression may not be applicable despite a correlation coefficient of 0.72 because of apparent lack of correlation in the lower dust concentration range (<1200 μg/m^3). Table 3 presents linear regression statistics for intercepts *b*, slopes *m*, and correlation coefficients *r* for dust concentration measurements using TEOM-TSP and UIUC-TSP samplers for all of the sites considered in this study. For the methods to be considered equivalent, an intercept close to zero and a slope close to one are needed. The intercept and slope range from −157 to 1903 μg/m^3 and from 0.7 to 1.5, respectively. Therefore, dust concentration measurements using TEOM-TSP and UIUC-TSP samplers were not equivalent for all of the sites.

Analysis of the Effect of Anisokinetic Sampling on TEOM Performance

The major factors contributing to particle loss during sampling are the anisokinetic sampling conditions and gravitational and inertial forces. Inertial losses may occur when the particles travel through a curve in the sampling tube, whereas gravitational losses may happen when the particles travel through the horizontal sections of the sampling tubing. Inertial and gravitational losses can be neglected, because the sampling line of the TEOM-TSP was straight, short, and vertical. Therefore, particle loss can be largely attributed to anisokinetic sampling.

Isokinetic sampling condition is achieved when the sampling probe is aligned parallel with the free gas stream (isoaxial), and the free gas stream velocity U_o is equal to the gas velocity entering the tube U (Figure 6a). In isokinetic sampling, the gas stream line flows directly into the nozzle without any deviation; thus, there is no particle loss at the inlet regardless of particle size or inertia. However, there could be gravitational settling losses between the inlet and the filter, and there could also be losses because of free-stream turbulence in the inlet in which the lateral motion of the particles (because of turbulence) caused them to impact the internal wall of the inlet. Isokinetic sampling, therefore, does not ensure particle sampling without losses; it does, however, ensure that the concentration and the size distribution of the particles entering the tube are the same as those in the flowing gas stream. When sampling is anisokinetic, the concentration and size distribution of particles are misrepresented, and the sampler may oversample or undersample large particles. Figures 6b and 6c show the nozzles sampling isoaxially under superisokinetic and subisokinetic sampling conditions, respectively. In superisokinetic sampling, the velocity in the nozzle inlet is higher than the gas stream velocity. In this condition, the gas stream lines converge into the nozzle; particles with sufficient inertia that are originally in the sampled air cannot follow the converging stream lines and are lost outside the sampler. The aspiration efficiency or the ratio of the particle concentration at the entrance of the sampler (C) and the particle concentration in the gas stream (C_o) is <1, and sampling under this condition underestimates the true concentration of the particles in the air. When the gas velocity of the gas stream exceeds that of the nozzle inlet velocity, the sampling condition is subisokinetic, and the gas stream lines diverge at the nozzle inlet. Consequently, particles with sufficient inertia that are outside the sampled air are aspirated by the sampling nozzle. In this case, the aspiration efficiency is >1, and it results in overestimation of particle concentration.

For properly aligned sampling inlets, the maximum error[16,17] during anisokinetic sampling is as follows:

$$\frac{C}{C_o} = \frac{U_o}{U} \qquad \text{for Stk} > 6 \tag{2}$$

and

$$\frac{C}{C_o} = 1 + \left(\frac{U_o}{U} - 1\right)\left(1 - \frac{1}{1 + Stk(2 + 0.62[U/U_o])}\right) \quad \text{for Stk} < 6 \tag{3}$$

where *Stk* is the Stokes inlet number and is defined by eq 4; ρ_o and d_a are the density and diameter of the particle, respectively; C_c is the slip correction factor; η is the air viscosity; and D_s is the nozzle diameter.

$$Stk = \frac{\rho_o d_a^2 C_c U_o}{18\eta D_s} \tag{4}$$

Table 3. Linear regression statistics for relationship between dust concentration measurements done using TEOM-TSP (independent variable) and UIUC-TSP (dependent variable) samplers.

	Linear Regression		Standard Error		
Site	**b**	**m**	**b**	**m**	**r**
Illinois	25.32	1.32	121.56	0.15	0.92
Iowa	1104.00	0.81	204.22	0.14	0.72
Indiana	1903.54	0.75	679.35	0.36	0.71
Minnesota	543.35	0.73	146.60	0.10	0.89
Texas	−157.14	1.54	429.17	0.22	0.88

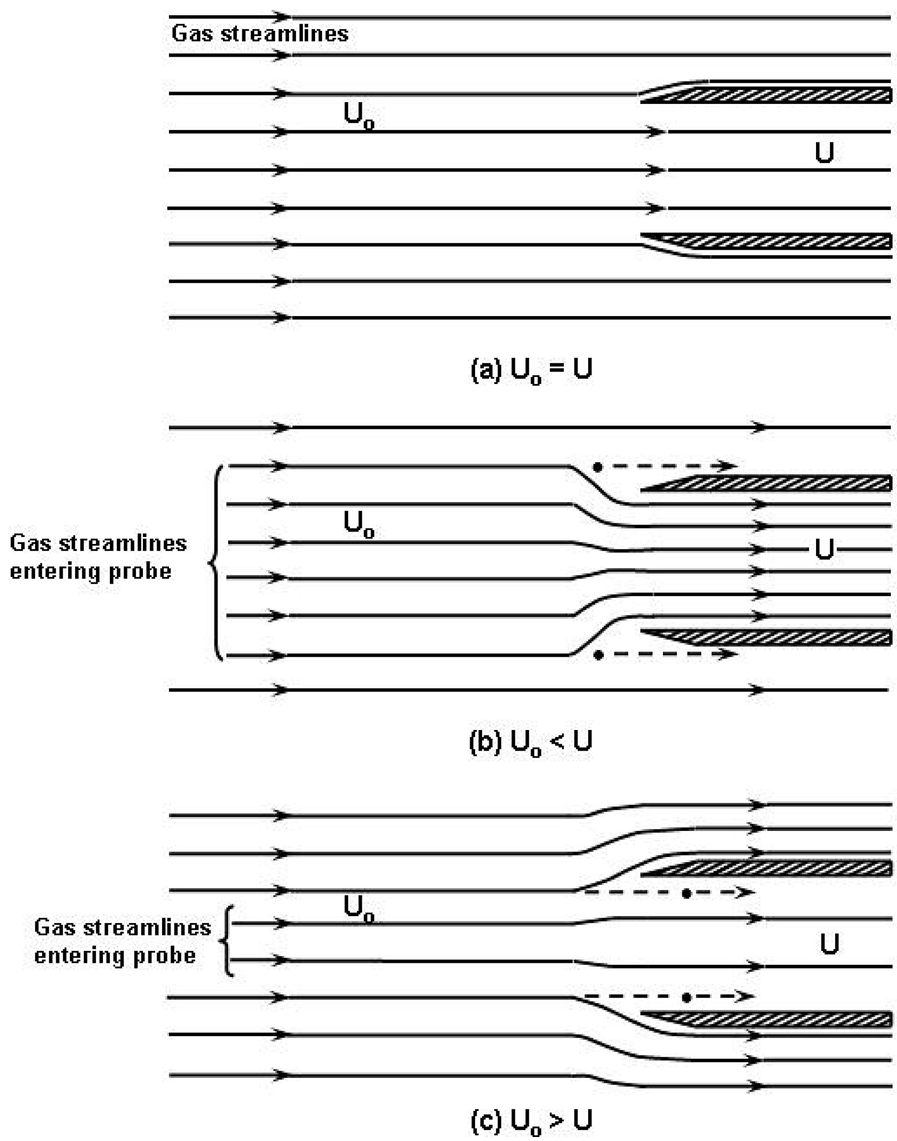

Figure 6. Schematic diagram of isoaxial sampling with a thin-walled nozzle under (a) isokinetic, (b) superisokinetic, and (c) subisokinetic sampling conditions.

Figure 7 shows the effect of velocity mismatch on the concentration ratio for different values of the Stokes number. Generally, the farther the concentration ratio is from 1, the greater is the loss of larger particles in the inlet; when Stk is 0.01, there was negligible particle loss ($C/C_o \cong 1$), regardless of the velocity ratio. The TEOM-TSP inlet was designed for an operational flow rate of 16.67 L/min, and the inlet area was sized to provide an effective particle capture velocity of 25 cm/sec resulting in an inlet diameter of ~4 cm. The calculated Stoke numbers for particle diameters of ≤100 μm at free-stream velocities of 0.25 to 2 m/sec are shown in Figure 8. It can be seen from the figure that even for a free-stream velocity of 0.25 m/sec, which matches the design inlet velocity of the TEOM-TSP, a Stk of <0.01 only holds for particles up to ~20 μm. As the free-stream velocity increased to 2 m/sec, only particles of ≤5 μm have a Stk of <0.01. Therefore, the collection efficiency of the TEOM-TSP for larger particles decreases with an increase in particle size resulting in significantly lower measured concentration compared with that of the UIUC-TSP isokinetic sampler.

CONCLUSIONS

TEOM-TSP and UIUC-TSP dust concentration measurements were compared for swine and chicken facilities in Illinois, Indiana, Iowa, Minnesota, and Texas for sampling periods between August 2003 and March 2004. The conclusions described below were drawn from this study.

The concentration of the total suspended PM measured in swine facilities ranges from ~250 to 2700 μg/m^3 for the TEOM-TSP monitor and from ~330 to 3700 μg/m^3 for the UIUC-TSP sampler; the measured dust concentration in a laying facility ranges from ~1520 to 2360 μg/m^3 for TEOM-TSP and 2940 to 4310 μg/m^3 for UIUC-TSP. In general, the measured dust concentration by TEOM-TSP was lower than those measured by UIUC-TSP by between 2% to 54%.

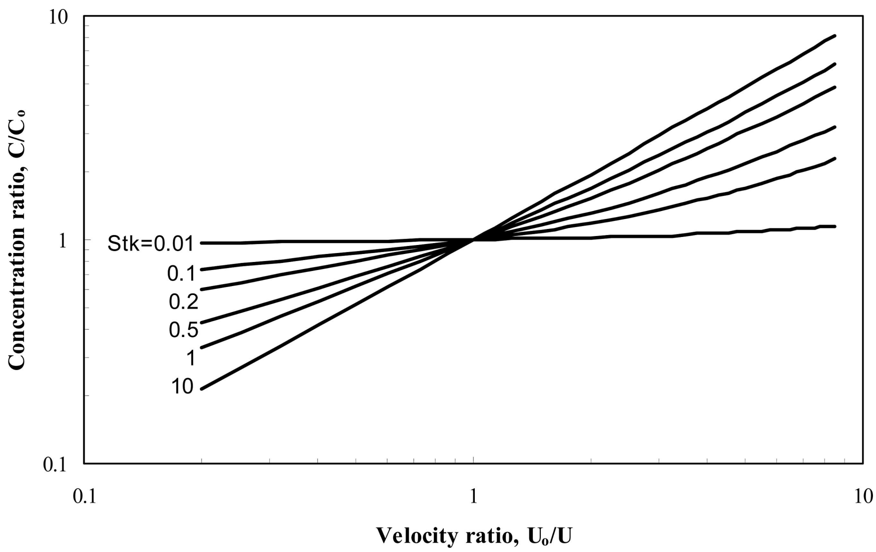

Figure 7. Effect of velocity ratio on concentration ratio for isoaxial sampling condition and different values of Stokes number.

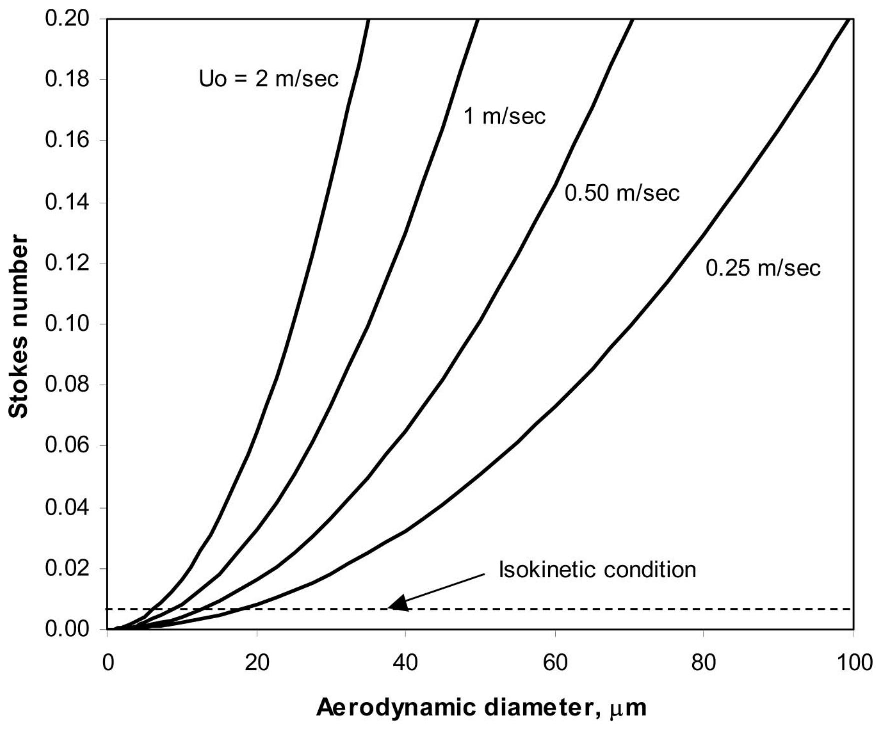

Figure 8. Relationship between the Stokes number and aerodynamic diameter of particles at different free-stream velocities. The isokinetic condition when there is a mismatch on free-stream and nozzle sampling velocities still holds when the Stokes number is <0.01.

Despite the scatter of the measurements at higher dust concentrations, the linear regression model clearly describes the relationship between TEOM-TSP and UIUC-TSP for the four sites monitored. The correlation coefficient for these four sites ranges from 0.71 to 0.92; the former was obtained for measurements done in Indiana in which a relatively high dust concentration was observed; correlation coefficients of ≥0.90 were obtained for the dust concentration measurements done in Illinois, Texas, and Minnesota, wherein the measured dust concentrations were relatively lower than those of Indiana.

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About the Authors

Sheryll B. Jerez and Joshua McClure are doctoral candidates and Yuanhui Zhang is a professor in the Department of Agricultural and Biological Engineering of the University of Illinois at Urbana-Champaign. Larry Jacobson is a professor in the Department of Biosystems and Agricultural Engineering of University of Minnesota. Albert Heber is a professor in the Department of Agricultural and Biological Engineering of Purdue University. Steve Hoff and Jacek Koziel are associate and assistant professors, respectively, in the Department of Agricultural Biosystems Engineering of Iowa State University. David Beasley is a professor in the Department of Biological and Agricultural Engineering of North Carolina State University. Address correspondence to: Sheryll B. Jerez, University of Illinois at Urbana-Champaign, Department of Agricultural and Biological Engineering, 1304 W Pennsylvania Ave, Urbana, IL 61801. phone: +1-217-244-6316; fax: +1-217-244-0323; e-mail: sjerez@uiuc.edu.