2011

Spatial and Temporal Distributions of Dust and Ammonia Concentrations in a Swine Building

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Abstract. *Pollutants, especially dust, are rarely uniformly distributed within ventilated air spaces due to non-uniform flow fields, particle inertia, gravitational settling, and diffusion. Thus, selecting suitable sampling locations for representative sampling is a challenge. The objective of this study was to determine the spatial and temporal distributions of dust and ammonia concentrations(NH_3) in a swine building. Results of this study are useful in the design of sampling strategies that require limited sampling locations and in studying pollutant transport. This study was conducted in a commercial swine building in Illinois. The total suspended particulate (TSP) matter and ammonia concentrations were measured at 50 and 30 indoor sampling locations in December and June, respectively. Results showed that the average TSP concentrations ranged from 0.86 to 3.81 mg m^{-3} in December and from 0.24 to 1.68 mg m^{-3} in June. In December, the dust gradient across the length of the building was more pronounced than along its length. In June, the gradient along the length of the building was more pronounced, resulting in essentially uniform concentration in a cross-section. The spatial distributions of the TSP concentrations in both December and June were essentially symmetrical about the longitudinal section of the building. The spatial gradient of NH_3 concentrations was more pronounced along the length of the building in December, while the spatial distribution was almost uniform in June. These results suggest that the choice of representative sampling locations indoors will vary depending on the air movement in the building, which is dictated by the ventilation scheme.*

Keywords. *Ammonia, Ammonia emission, Animal housing, Dust, Emissions, Particles, Spatial variability, Swine.*

Indoor air quality in animal buildings must be maintained at levels not detrimental to the health and well-being of workers and to the development and productivity of animals. One of the effective and practical ways of achieving acceptable indoor air quality is the application of ventilation control, i.e., varying the ventilation rate, and the configuration and location of air inlets. The effectiveness of a ventilation system, as well as other control measures (e.g., oil sprinkling, dust deduster, wet scrubber, etc.) can be characterized by how well it removes pollutants from representative locations. Since pollutants, especially particles, are rarely uniformly distributed within ventilated air spaces due to non-uniform flow fields, particle inertia, gravitational settling, and diffusion (Brockmann, 2001; Wang, 2000; Zhang, 2005; Zhang et al., 1994; Zhang et al., 1998), selecting suitable locations where the pollutants will be measured is a major consideration for indoor air sampling.

When considering where to sample pollutants indoors, researchers tend to choose sampling locations near the center of the building and at the breathing level of either the animals or the workers to determine the average pollutant concentrations in animal confinement buildings (e.g., Achutan et al., 2001; Kim et al., 2005; Maghirang et al., 1997; Predicala et al., 2001). Maghirang et al. (1997) monitored dust concentrations and particle size distributions at three sampling locations in a swine nursery and reported spatial variability in total dust concentration. In a separate study in two swine finishing buildings in Kansas, Predicala et al. (2001) reported spatial variability in dust and bioaerosols within and between the buildings. In studies with more than one sampling location, results vary depending upon how the sampling sites were chosen (Barber et al., 1991). When the spatial distribution of contaminants is found to be uniform, as was the case in the study on spatial distribution of aerial pollutants in a deep-litter pullet house done by Conceicao et al. (1989), randomly chosen locations can be considered representative. However, spatial homogeneity of pollutant concentration, especially for particles, is a rarity (Barber et al., 1991).

In other reported spatial distribution studies conducted in commercial animal facilities, significant variation in the concentration of particles and gases indoors was found. Barber et al. (1991) measured dust concentration at 16 sampling locations distributed within the half-section of a grower-finisher piggery. They found less variability in dust concentration from end-to-end of the building than within the building cross-section. Wang et al. (2002) monitored 27 sampling points in the central cross-section of an empty pig building for spatial distribution of dust concentration. They reported high variation in dust concentration among the sampled locations, and this variation was affected by the ventilation rate and diurnal change. Variation in dust concentration among the 25 sampling locations inside a fattening piggery was also reported by Hinz and Linke (1998), with

Submitted for review in September 2010 as manuscript number SE 8794; approved for publication by the Structures & Environment Division of ASABE in September 2011. Presented at the 2010 ASABE Annual Meeting as Paper No. 1009314.

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  ISSN 2151-0032

lower dust concentration observed in the aisle than over the pens; the spatial distribution of ammonia (NH_3) concentration, however, was almost uniform. The findings by Barber et al. (1991), Hinz and Linke (1998), and Wang et al. (2002) clearly contradict the results presented by Conceicao et al. (1989), who reported spatial homogeneity of inspirable dust concentration and spatial heterogeneity of measured NH_3 concentrations. Direct comparisons of the aforementioned studies, however, may be misleading since they were conducted in different types of animal buildings with different air distribution patterns.

The spatial distribution of airborne pollutants is not only useful in the design of sampling strategies that require limited sampling locations but also for the study of pollutant transport indoors. Only when the transport of airborne pollutant is clearly understood can a successful control strategy, i.e., modification of the design of the ventilation system, be realized. The main objective of this study was to measure and analyze the spatial and temporal variations of the concentrations of total suspended particulate (TSP) matter and NH_3 in a commercial swine building. Results of the spatial and temporal measurements were used to determine the best representative locations in the building when a limited number of samplers is available and the optimum sampling duration to account for the diurnal difference in activities in the building.

Experimental Details

Description of the Swine Building

The swine facility, located in McLean, Illinois, has nine wean-to-finish buildings with a total capacity of 12,000 head. Measurements were conducted in one of the nine buildings containing approximately 2300 pigs in December 2005 (winter) and 2400 pigs in June 2006 (summer). The building was 64.6 m long, 12.2 m wide, and 4.7 m high. Pigs were brought in when they were approximately three weeks old, weighing close to 5 kg, and they were fed until reaching a market weight of about 115 kg. The entire production period took about 24 weeks, with the first 8 to 10 weeks for nursery and the next 14 to 16 weeks for raising the pigs to market weight. The pigs were weighed three times: at 0, 10, and 20 weeks post-weaning. These weight data were used to obtain the approximate growth curve of the pigs. Based on the growth curve, an average daily gain of 0.76 kg d^{-1} was obtained. The feed diet was about 61% corn, 22.5% dried distiller grain, about 13% beanmeal, and trace amounts of white grease, limestone, salt, copper sulfate, lysine, Hanor hog VTM/Finisher, Decal, Threonine, and Linco 50.

The building that was used for measurements had 40 pens (3.3 × 5.7 m) with a completely slatted floor. It had a 2.4 m deep pit underneath the floor where manure was stored for approximately one year and applied to the field thereafter using a drag hose system. The pens, which had 30 to 50 pigs each, were in two rows with 20 pens in each row (fig. 1). Feed tanks were present between every two pens. Pigs were fed through feed contained on mats placed in each pen.

Figure 1 presents a schematic of the building cross-section showing the location of the ceiling inlets, and exhaust and pit fans. The building was mechanically ventilated with five-staged exhaust fans consisting of one variable-speed 91 cm fan, four single-speed 122 cm fans, and four single-stage, continuously running 46 cm pit fans. All fans had discharge diffuser cones and gravity-controlled shutters. The building was tunnel-ventilated during warm weather with air drawn through electronically controlled curtains in the end wall opposite the exhaust fans. During mild weather, partial ventilation was also provided by the ceiling inlets. In winter, the building was ventilated through 13 baffled-type ceiling inlets installed over the central walk alley; each inlet was 240 cm long and 40 cm wide. The building had sidewall curtains for emergencies, i.e., when power interruption occurs, the sidewall curtains prevent heat, moisture, and dust buildup inside the building.

Sampling Locations

The sampling locations for both TSP and NH_3 are shown in figure 2. The spatial distribution of TSP was measured at five cross-sectional planes (represented by Roman numerals I, II, III, IV, and V) in figure 2, which were 12.8 m apart; the cross-sectional planes were at distances of x = 7.0, 19.8, 32.6,

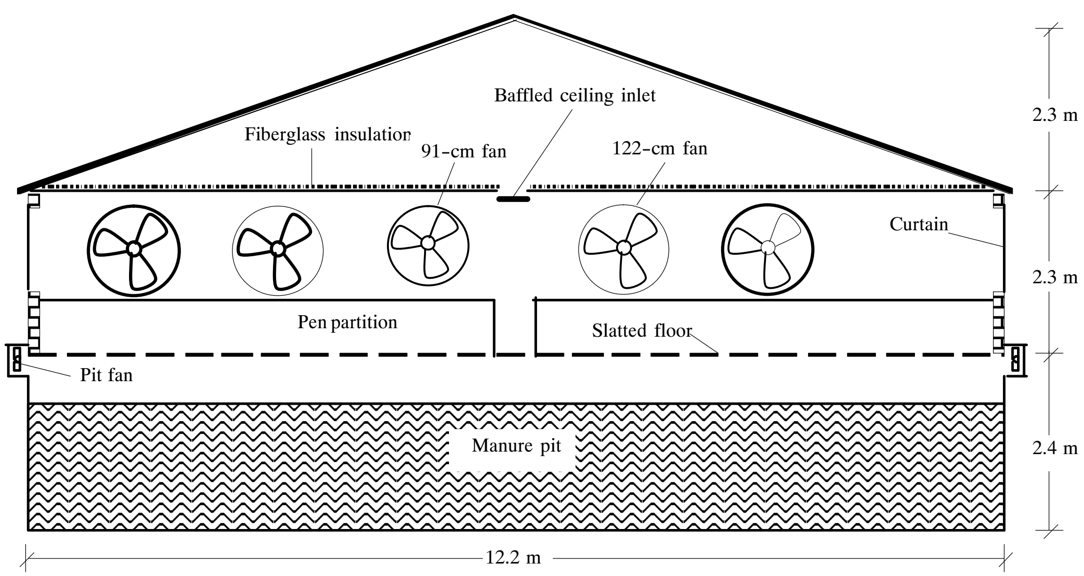


Figure 1. Schematic of the cross-section of the swine building.

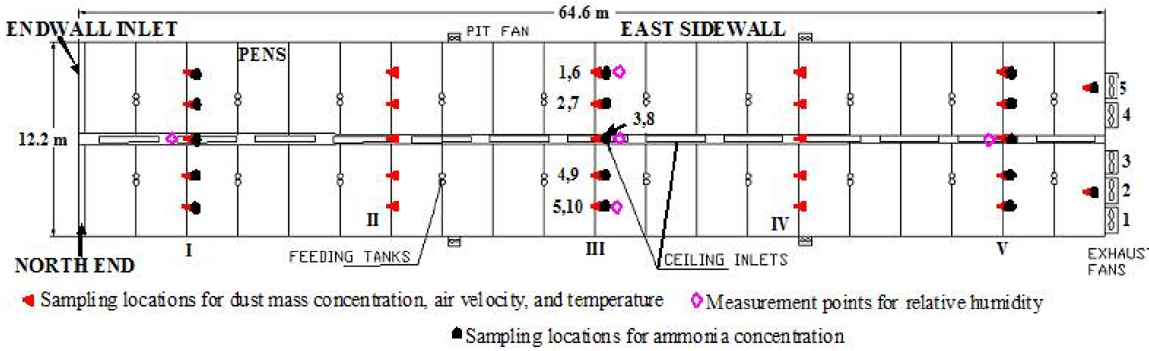


Figure 2. Plan view showing the sampling locations for TSP.

45.4, and 58.2 m from one end of the building. There were ten sampling locations in each plane with five samplers (1, 2, 3, 4, and 5) located at z = 1.6 m from the floor and the other five (6, 7, 8, 9, and 10) located at z = 0.8 m. Eight of the samplers (1, 2, 4, 5, 6, 7, 9, and 10) were over the pens, while the other samplers (3 and 8) were in the central alley. For each cross-sectional plane, the samplers were located at y = 2.04 (samplers 1 and 6), 4.08 (samplers 2 and 7), 6.12 (samplers 3 and 8), 8.16 (samplers 4 and 9), and 10.2 m (samplers 5 and 10) from the east sidewall of the building. These sampling locations are referred to in the text by the cross-sectional plane and the sampling location number (e.g., I-10). For the measurement of NH_3 concentrations, the same 30 sampling locations in planes I, III, and V used for the TSP measurements were monitored sequentially. The concentrations of both NH_3 and TSP leaving the building were monitored at about 0.75 m upstream of the two 122 cm fans. The inlet concentrations of TSP and NH_3 were monitored at the ceiling inlet in December and at both ceiling and end wall inlets in June.

Dust Sampling System

The multipoint dust measurement system consisted of open-face filter holders, critical venturis, and a 746 W sampling pump. The open-face 37 mm diameter cassette-type filter holder served as both the inlet and filter holder. The samplers were oriented horizontally, with the inlet facing toward the north end of the building; with this orientation, the primary airflow during summer was expected to be parallel to the filter holder plane, minimizing the effect of differing degrees of non-isokinetic sampling. During winter, the air inside the building was calm (air velocity was less than 2.5 cm s^{-1}), and the horizontal sampler orientation prevented error due to gravitational settling. The critical venturi was located downstream of the filter and controlled the flow rate through the filter at a constant rate of 0.022 ±0.0002 m^3 min^{-1} (21.85 ±0.20 L min^{-1}) at a critical pressure of 10.21 ±0.90 kPa. A detailed description of the venturi is presented by Wang and Zhang (1999).

The sampling setup for the measurement of TSP concentration is shown in figure 3. This setup consisted of a ten-point measuring array, and five replicates of this setup were constructed to measure 50 sampling locations simultaneously. The main sampling line was a 19.1 mm chlorinated polyvinyl chloride (CPVC) pipe, while the branches were 12.7 mm CPVC pipes. A 101.6 mm long, 12.7 mm diameter CPVC pipe connected the critical venturi to the branch. A 50.8 mm long vinyl tube connected the filter holder to the critical venturi. For ease of transport and installation, the main and secondary pipes were constructed in sections, i.e., the main pipe consisted of four sections, while the secondary pipe was divided into two sections. The main section was connected to a 746 W (1 hp) vacuum pump. At locations upstream of exhaust fans 2 and 5 in figure 2, dust concentration was measured using the isokinetic sampling system presented by Jerez et al. (2006).

The mass concentration of TSP was measured by collecting dust onto either glass fiber (1.6 μm porosity, Whatman Type GF/A) or Teflon (2 μm porosity, Zefluor PTFE membrane) filters at an average flow rate of 0.02 m^3 min^{-1}. Glass fiber filters were used solely for mass concentration measurements, while Teflon filters were used for both mass concentration and particle size distribution (PSD) measurements. Results of the PSD measurements are presented in another article. Prior to and after dust collection, the filters were conditioned in a dessicator (temperature of 20°C ±2°C and relative humidity of 15% ±5%) for at least 24 h. The filters were weighed before and after sampling with a high-precision analytical balance (readability of 0.01 mg, Mettler

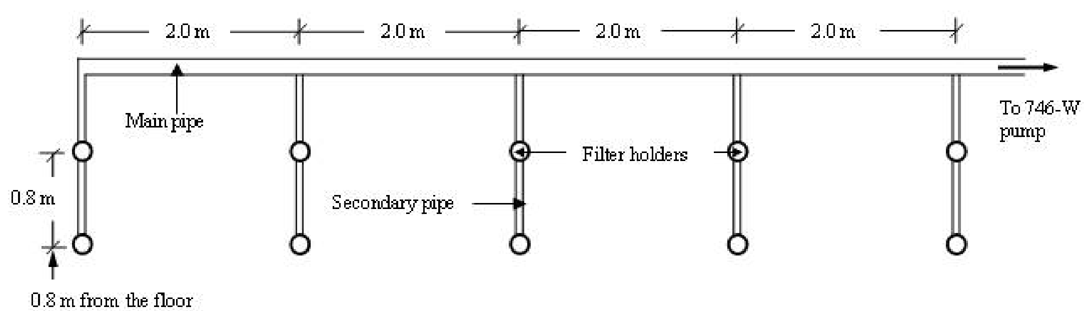


Figure 3. Schematic of the TSP sampling system.

Toledo, Greifensee, Switzerland). The critical venturis were also calibrated prior to use with an automated venturi calibrator. The calibrator consisted of an accurate flow metering device (Drycal BIOS model DC-2M, BIOS International, Butler, N.J.), a pump, a pressure control unit, and a personal computer. The actual flow rates through the venturis when installed in the sampling setup in the farm were also measured using the Drycal BIOS.

TSP was measured during winter (December 7-16, 2005) and summer (June 14-28, 2006). Two sets of samples were collected each day: one set to measure the daytime concentration, and the other set was for nighttime concentration. Daytime sampling ran from about 06:00 h to about 18:00 h, and nighttime sampling was from about 18:00 h to about 06:00 h of the following day.

Ammonia Sampling System

A schematic of the NH_3 measurement system is shown in figure 4. It consisted of three stainless steel, five-way valves (Swagelock, Solon, Ohio) mounted on a plastic panel, Teflon tubing, and quick-connect fittings. The plastic panel was mounted on top of a wheeled cart containing the NH_3 analyzer (model 17C, TEI, Franklin, Mass.) for quick transport of the measurement system from one cross-sectional plane to the next. Valves 1 and 2 were directly connected to the sampling lines through quick-connect fittings. The outlet port of valve 3 was connected to the NH_3 analyzer, while its two inlet ports were connected to the outlet ports of valves 1 and 2. Each valve has a lever on top that was used to manually open and close each port, i.e., when one inlet port was open, the other three inlet ports were closed, while the outlet port remained open. In sampling lines 1 to 4, for instance, the inlet port of valve 3, which was the passage for stream A, was open, while the inlet port for stream B was closed, and vice versa for sampling lines 5 to 7.

The sampling lines were 19.1 mm diameter fluorinated ethylene-propylene (FEP) tubing and varied in length from about 5 to 12 m. A 47 mm perfluoroalkoxy (PFA) filter holder containing a polytetrafluoroethylene (PTFE) membrane filter (0.45 μm pore size, Savillex Corp., Minnetonka, Minn.)

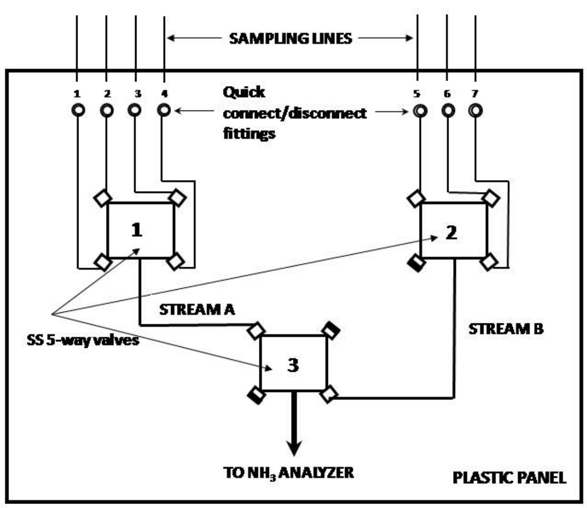


Figure 4. Schematic and components of the ammonia sampling system. Only four ports of each five-way valve are shown; the fifth port, which is the outlet, is at the bottom.

was located on the intake side of every sampling line to filter out dust in the sampled air. The NH_3 concentration in the filtered air was analyzed using a chemiluminescence NH_3 analyzer (model 17C, TEI, Franklin, Mass.). The low detection limit of this analyzer is 1 ppb, and it can measure up to 100 ppm.

The spatial concentration of NH_3 was monitored sequentially, in random order, and at one sampling plane at a time, i.e., after all ten sampling locations in one plane were monitored, the next sampling plane was monitored. Ten concentration readings, with a frequency of 15 s, were collected at each sampling location, and a stabilization period of 3 min or until the concentration stabilized to within 0.5 ppm was applied when switching from one location to the next. The measured concentrations were recorded manually. Prior to measurement, the analyzer was calibrated at an NH_3 concentration range of 0.5 to 30 ppm.

The spatial distribution of NH_3 was monitored simultaneously with the dust spatial distribution measurement but only for five days each during the winter (December 7-16, 2005) and summer (June 14-28, 2006) sampling periods. During each sampling day, monitoring began between 09:00 h and 13:00 h and lasted at least 3 h.

Measurement of Environmental Parameters

The air temperature at 50 sampling locations indoors, three inlet locations, and five exhaust locations were monitored every 60 s using copper-constantan thermocouples (type-T) connected to four dataloggers (models CR21X and CR23X, Campbell Scientific, Inc., Logan, Utah). Fifty-four PVC-insulated 20-gauge (0.81 mm conductor size) type-T thermocouples were used. This type of thermocouple has a measurement range of 0°C to 370°C, an accuracy of 1°C or ±0.75%, and a response time of 15 s. The thermocouples were calibrated prior to use at a measurement range of 0°C to 40°C using a dry-block calibrator (model PB-35L, Techne (Cambridge) Limited, Duxford, U.K.) and a CR23X datalogger (Campbell Scientific, Inc., Logan, Utah) connected to a computer.

The ventilation rate in the building (Q_b) was monitored continuously using impeller anemometers installed downstream of the fans but inside the fan cones. Each anemometer (model 27106, R.M. Young Co., Traverse City, Mich.) was used to estimate the total flow rate through a fan by measuring the airspeed at a representative location. The specific locations of the anemometers *in situ* were predetermined during the calibration in the laboratory. The impeller anemometer consisted of an 18 cm diameter vane attached to a sealed bearing, direct current (DC) generator that produced a 0 to 1 VDC output proportional to the rotational speed. Prior to using the anemometers, they were calibrated in the fan test chamber in the Bioenvironmental Engineering Structure Systems (BESS) laboratory at the University of Illinois at Urbana-Champaign.

Air velocity in all sampling locations was measured before and after each sampling using a hot-wire anemometer (model 8340, TSI, Inc., Shoreview, Minn.). This anemometer has a measurement range of 0 to 10 m s^{-1} with an accuracy of ±0.025 m s^{-1}. It was calibrated prior to use in the field using a wind tunnel (model 8390, TSI, Inc.) at a measurement range of 0.15 to 4.10 m s^{-1}.

The airflow pattern in the swine building was visualized by generating smoke inside using a portable oil-based smoke generator. Mineral oil (USP grade, available as baby oil, Johnson and Johnson) was used as the fluid. Smoke was generated continuously for more than 10 min in one section of the building at a time. Since it was impossible to trace the air movement from one end of the building to the other end by generating smoke in one location only, smoke was generated at several locations until a clear airflow pattern was established.

Data Analyses

The weight of dust collected on the filter was the difference between the weight of the loaded filter and its clean weight before sampling. The dust concentration was the mass of dust collected divided by the total volume of the sampled air. The total volume of sampled air was the product of the flow rate of the venturi and the total sampling time. Field blanks (filters enclosed in filter holders that were exposed to all aspects of sampling except collection) were also collected during sampling to measure incidental or accidental sample contamination during the whole process (sampling, transport, sample preparation, and analysis). The mass of dust collected on the field blanks ranged from 0.00 to 0.10 mg. The average amount of dust collected from the field blanks was subtracted from the collected dust mass.

Several linear procedures in SAS (SAS, 2008) were used in the data analyses. Among these procedures were PROC TTEST, PROC GLM, and PROC MIXED. The PROC TTEST procedure was used to test the significance of the differences between the means from two independent samples. Specifically, PROC TTEST was used to compare the means of daytime and nighttime dust concentration and temperature, and the means of dust concentration at elevations of 0.8 and 1.6 m. The PROC GLM and PROC MIXED procedures were used for the analysis of variance (ANOVA) to determine if the differences in the means from various sampling locations were significant and to calculate the 95% confidence limits of the means. In addition, a pairwise comparison of the means of adjacent sampling locations within each elevation was done using the least significant difference method of ANOVA.

Results and Discussion

Ventilation Rates

The ventilation rate is the volume of outside air introduced into the building per unit time. Air rushed through the inlets because of the negative pressure created by the exhaust fans. During summer, when the endwall inlet was open, air also rushed through the inlet due to wind pressure.

During the winter sampling, all exhaust fans were off except on December 14 and 15 when one fan was on. Two of the pit fans were on throughout the sampling period. The 24 h average ventilation rate for the building ranged from 0.76 to 3.73 $m^3 s^{-1}$. The actual 24 h, daytime (06:00 h to 18:00 h) and nighttime (18:00 h to 06:00 h) average ventilation rates in December are shown in figure 5. The ventilation rates at daytime and nighttime did not vary significantly, with values ranging from 0.75 to 3.71 $m^3 s^{-1}$ for daytime and from 0.77 to 3.85 $m^3 s^{-1}$ for nighttime. In six out of ten days, the daytime average ventilation rates were higher than the nighttime averages by as much as 31%. The ventilation rate was nearly constant during the first five days of sampling and started to increase the following four days, peaking on December 14. The corresponding daily averages of outdoor temperature (T_o) are also shown in figure 5. The daily average T_o ranged from -9.7°C to 13.2°C. In general, an increase in T_o was accompanied by an increase in ventilation rate to maintain an approximately constant temperature of 25°C inside the building.

The daily, daytime, and nighttime averages of ventilation rates measured in June are presented in figure 6. The daily average ventilation rates ranged from 23.21 to 46.03 $m^3 s^{-1}$. The maximum daily ventilation rate in June was more than ten times the maximum value in December. This wide variation in ventilation rates was expected since the outside temperature fluctuates throughout the year and the operation of the fans has to be adjusted to maintain a constant temperature inside the building. In a one-year measurement study conducted in swine finishing buildings with 1100 pigs, Heber et al. (2004) reported ventilation rates ranging from 1.57 to 38.5 $m^3 s^{-1}$, which were close to the results of this study. The daytime and nighttime averages ranged from 14.71 to 44.27 $m^3 s^{-1}$ and from 31.71 to 47.79 $m^3 s^{-1}$, respectively. Unlike the winter measurements, the daytime and nighttime

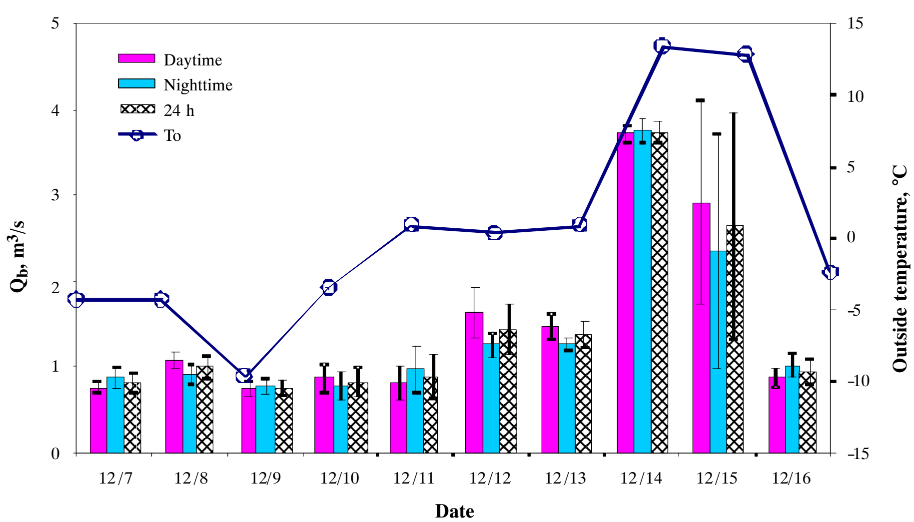


Figure 5. Daytime, nighttime, and 24 h averages of ventilation rates, and the average daily outside temperature (T_o) in December. The error bars represent standard deviations of measurements.

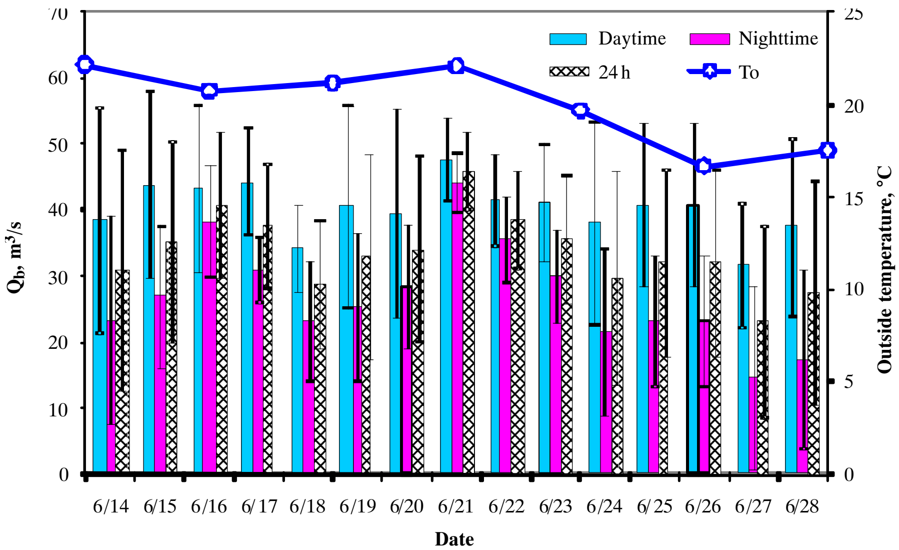


Figure 6. Daytime, nighttime, and 24 h averages of ventilation rates, and the average daily outside temperature (T_o) in June. The error bars represent standard deviations of measurements.

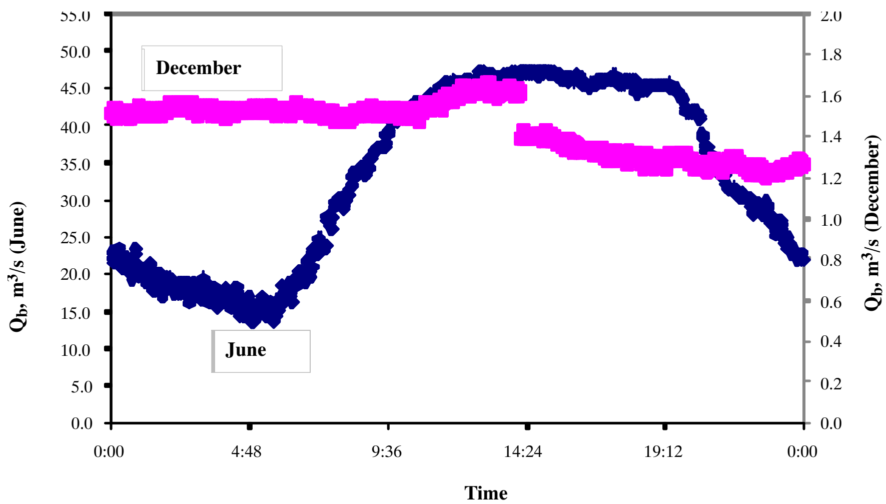


Figure 7. Diurnal variation of the average ventilation rate in the December and June sampling periods. The values are averages over all sampling days.

ventilation rates were significantly different ($p < 0.05$) from each other; the daily daytime averages were consistently higher than the measured nighttime ventilation rates by as much as 54%. The outside temperature also fluctuated throughout the measurement period, with the daily averages ranging from 16.5°C to 22.1°C.

Figure 7 shows the diurnal variation in ventilation rate of the building in the December 2005 and June 2006 sampling periods. The values plotted in the figure are averages over all sampling days. As shown in the figure, the ventilation rate in December was almost constant throughout the day (variation did not exceed 0.5 $m^3 s^{-1}$). During winter, only the pit ventilation fans were in operation most of the time, and these fans were single-speed. In June, however, both the pit and the exhaust fans were in operation. The number of exhaust fans that were on also varied depending on the temperature inside the building. Thus, the ventilation rate in June varied throughout the day. The ventilation rate was lower from midnight until about 05:00 h, and it increased afterward, peaking around noontime. The ventilation rate decreased after 19:00 h.

Spatial Distribution of Temperature and Air Velocity

The daily mean temperature inside the swine building did not vary significantly, ranging from 21.8°C to 24.8°C in December, with a coefficient of variation (CV) of 11.8% to 15.5%. In June, the daily average temperature inside the swine building ranged from 24.0°C to 28.2°C, with a lower CV ranging from 4.2% to 8.0%. The higher CVs in December indicate that the temperature inside the barn was less uniform in December than in June, which can be attributed to the presence of supplemental heaters (an electric heater and heat lamps that provide additional heat to the pigs) inside the building during winter. The electric heater was located in the right section of the building at about 20 m from the north end (plane II). The maximum indoor temperature in December was 40.6°C, while it was 31.3°C in June. The maximum temperatures occurred at II-10 and V-9 for December and June, respectively. Analysis of variance showed that the mean temperatures at 0.8 m and 1.6 m from the floor did not vary significantly at the 5% level for both December and June.

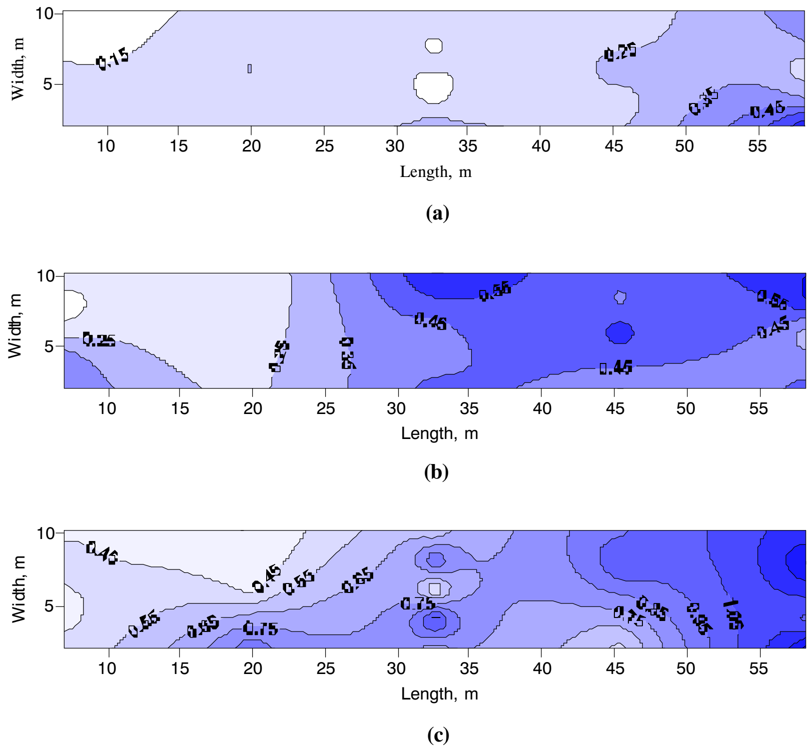


Figure 8. Contours of the air velocity (m s^{-1}) at three fan settings: (a) fans 1 and 3 on; (b) fans 1, 3, and 5 on; and (c) all fans on. All measurements were done at 1.6 m from the floor. Refer to figure 2 for the fan number designations. Data were plotted using Surfer version 7, which uses the weighted average interpolation algorithm.

The air velocities at the inlet and indoor sampling locations were also recorded for the December and June sampling periods. It should be noted that the air in the room was calm in December, and the air velocities at the sampling locations were close to zero and below the measurement range of the hot-wire anemometer. In addition, the air velocities at the air inlets and indoors were only measured before and after each sampling period each day, and the presented values may not represent the daily average condition since the building ventilation rate varied throughout the day, and the wind velocity and direction outside of the building also affected the inlet air velocity. The average inlet air velocity in December ranged from about 0.19 to 0.51 m s^{-1} with a CV of about 10% to 20%. In June, it was 4.13 to 5.74 m s^{-1} with CVs ranging from about 6% to 35%.

The air velocities at the sampling locations averaged over all sampling days in June were about 0.38 to 1.22 m s^{-1} with CVs of about 46% to 88%. Since the air velocities were only measured before and after each sampling event, there was a huge variation over the average air velocity values. For some perspective on how the velocity distribution varies in the building as the number of fans in operation changes, the spatial distribution of the measured instantaneous air velocities at three fan settings (corresponding to three levels of ventilation rates) are presented in figure 8. The air velocity data that were used in this figure were obtained during three different days of sampling, but the time of measurement was only separated by about 20 min; all measurements were done before the daytime sampling commenced.

In figure 8a, the resulting spatial velocity distribution was almost uniform except for the occurrence of relatively higher air velocities at the lower right corner of the figure, which was close to the location of exhaust fans 1 and 3. When three fans (1, 3, and 5) were on, the spatial distribution of the air velocity was still relatively uniform in most parts of the building, especially near the front end. In figures 8a and 8b, the endwall inlet was closed while the ceiling inlets were partly open. When all exhaust fans were on, as is the case in figure 8c, the endwall inlet was open by about 31 cm, which resulted in higher air velocity close to the endwall inlet compared to when this inlet was close (0.5 vs. 0.25 m s^{-1}). The air velocity also increased from the endwall inlet to the exhaust fan.

Spatial Variation of TSP Mass Concentration

Variation Along and Across Building Length

In December, out of 350 samples, six were lost due to pig intervention. In June, the total number of lost samples was 37 out of 750 samples. For the measurements in December, the dust mass concentration measured at each sampling location ranged from 0.31 to 6.92 mg m^{-3}. In June, the minimum measured mass concentration was 0.07 and the maximum was only 2.75 mg m^{-3}.

The average mass concentration of TSP at each sampling location is presented in table 1. The statistics presented in the table were calculated from combined daytime and nighttime samples in December 2005 and June 2006. The average mass concentration ranged from 0.85 to 3.81 mg m^{-3} in December and from 0.24 to 1.68 mg m^{-3} in June. The overall mean dust concentration inside the building in December was 274% higher than in June (2.25 vs. and 0.82 mg m^{-3}). The CVs of the average mass concentration for each sampling location ranged from about 20% to 61% in December and from about 20% to 92% in June.

The results of the pairwise analysis are shown in table 1. The mean dust concentrations among the sampling locations within each cross-section and elevation were significantly

Table 1. Comparison of the means of the TSP mass concentration (mg m^{-3}) at each sampling location at elevations of 0.8 and 1.6 m in December and June.[a]

Elevation and Sampling Location		December 2005, Cross-Section					June 2006, Cross-Section				
		I	II	III	IV	V	I	II	III	IV	V
1.6 m	1	1.90 b	1.91 b	1.02 b	1.48 b	1.32 bc	0.27 bc	0.52 c	0.53 b	0.72 c	0.74 c
	2	3.33 a	2.87 a	2.82 a	2.48 a	2.31 a	0.36 abc	0.79 b	1.01 a	1.32 a	1.34 ab
	3	2.89 a	2.27 a	1.65 b	2.22 a	1.89 ab	0.39 ab	0.98 a	1.11 a	1.15 b	1.43 a
	4	3.47 a	3.04 a	2.73 a	2.89 a	1.69 ab	0.43 a	0.99 a	1.07 a	1.18 ab	1.24 b
	5	1.83 b	1.57 b	1.22 b	1.57 b	0.86 c	0.24 c	0.60 c	0.48 b	0.59 c	0.71 c
0.8 m	6	2.21 b	2.92 a	2.05 bc	1.48 c	1.79 bc	0.30 b	0.53 c	0.62 c	0.68 c	0.73 c
	7	3.67 a	3.24 a	2.79 ab	2.66 ab	2.60 a	0.37 ab	0.85 b	0.96 b	1.08 b	1.31 b
	8	2.60 b	1.94 b	1.74 c	2.24 abc	1.94 ab	0.45 a	1.12 a	1.18 a	1.26 a	1.68 a
	9	3.81 a	3.07 a	2.90 a	2.97 a	1.78 bc	0.47 a	0.96 ab	1.06 ab	1.20 ab	1.49 ab
	10	1.77 b	1.94 b	2.12 abc	1.94 bc	1.08 c	0.27 b	0.62 c	0.56 c	0.63 c	0.68 c

[a] Means followed by the same letter within the same column (i.e., cross-section) for each elevation are not significantly different at the 5% level.

different at the 5% level. The mean dust concentrations over the pen closer to the central alley at 1.6 m (sampling locations 2 and 4) in all cross-sections were consistently higher than the means at sampling locations closer to the sidewalls (sampling locations 1 and 5). In addition, sampling locations 2 and 4 were not significantly different from each other, as is true for sampling locations 1 and 5. At the lower elevation (0.8 m), however, the only clear trend was that the means at sampling locations 7 and 9 were higher than those at sampling locations 6 and 10, but the difference, in most cases, was not significant at the 5% level. The mean dust concentration at the central alley at an elevation of 1.6 m was not significantly different from the means at sampling locations 2 and 4 except at cross-section III (the longitudinal midsection of the building). At the lower elevation, the mean dust concentration at the alley (sampling location 8) was, in general, not significantly different from the mean dust concentrations at sampling locations 6 and 10. These results suggest that during winter, when there was virtually no airflow in the building, the variation in the TSP mass concentration across the length of the building was significant due to the location of the feed, the condition of the pens, and the level of activity in the building. In general, the mass concentration at different locations in the same pen (e.g., locations 1 and 2) are more likely to vary compared to the corresponding locations in the opposite pen (e.g., locations 4 and 5). As shown in figure 9, the mass distribution on half the width of the building almost mirrored the other half. Thus, if a limited number of sampling locations is desired, the samplers could be distributed on half of the width of the building over the pens and alley.

Barber et al. (1991) measured the spatial distribution of the TSP mass concentrations at 16 sampling locations in an occupied grower-finisher piggery in Canada that was ventilated through the ceiling inlets and with exhaust fans on the sidewall. Similar to this study, they reported significantly higher dust concentration toward the front of the pens (or close to the central alley) than at locations closer to the sidewalls. The spatial variability they observed is consistent with the general understanding that dust is expected to be higher where it is produced and the distribution is affected by the prevailing airflow. In Hinz and Linke (1998), inhalable dust (particle diameter of $\leq$100 μm) concentrations were lower in the central alley than in the pens of a fattening piggery in Germany. This difference is attributed to the air movement in the building. In the Hinz and Linke (1998) study, the exhaust fans were mounted in separate exhaust ducts along the roof of the building, whereas in Barber et al. (1991) and in this study, the exhaust fans were located on the sidewall and endwall, respectively.

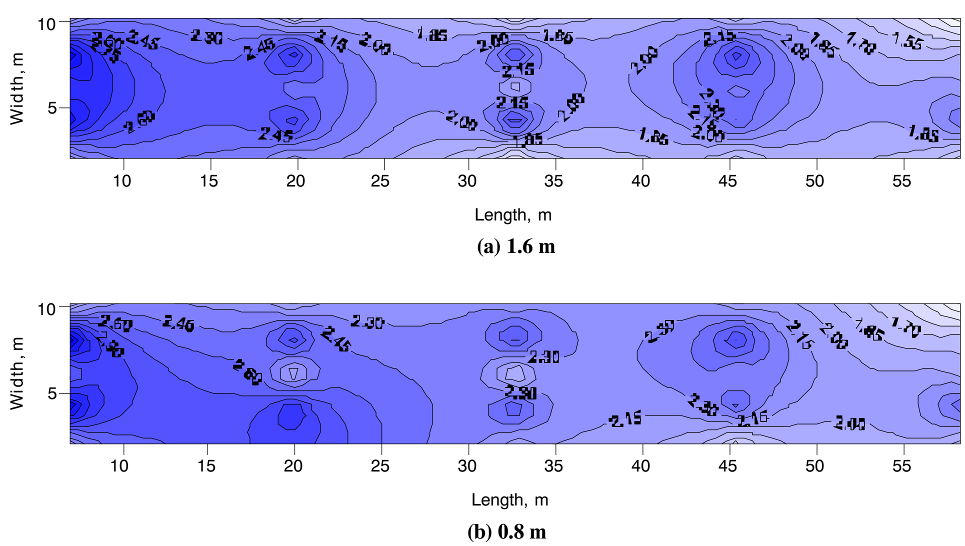


Figure 9. Spatial distribution of the average TSP mass concentration (mg m^{-3}) measured in December at elevations of (a) 1.6 m and (b) 0.8 m. Data were plotted using Surfer version 7, which uses the weighted average interpolation algorithm.

The contours of the spatial distribution in December are plotted in figure 9. The spatial distributions of mass concentration measured at elevations of 1.6 and 0.8 m from the floor were similar. Across the width of the building, the mass concentration of dust was generally higher over the pens close to the central alley (at building widths of about 4 and 8 m) than toward either sidewall of the building. High concentration at these locations can be attributed to the location of the feeder. As shown in figure 2, there were feeding tanks located over the pens at widths of about 4 and 8 m. The TSP mass concentration over the alley was also generally higher (not significant) than at locations closer to the sidewalls due to its proximity to the dust source from the feed mats on the floor and the dried feces in the alley. In addition, the higher dust mass concentration measured over the alley can also be attributed to the activities of researchers and workers, which caused resuspension of feed and fecal dust particles on the floor. The lowest dust concentration was measured at locations near the sidewalls, where the floors were wet with urine from the pigs. The floors near the sidewalls were wet most of the time, since very little airflow was able to reach those locations during winter. The cold air jets entering the ceiling inlets fall immediately over the central alley and toward the manure pit.

There was also a low mass concentration of TSP near the midsection of the building, which could be attributed to dry, feces-free, and feed-free floors because this is where the sick pens (where pigs with both health and physical problems, separated from the rest of the pigs, were relocated) were situated. Since the sick pens were occupied by fewer pigs (fewer than ten at anytime), there were less activities in these pens.

Along the length of the building in figure 9, there was higher dust buildup close to the front end (length zero in the figure), and the concentration diminished toward the opposite end. Barber et al. (1991) reported higher dust concentrations at both ends of the building than in the middle. However, they cautioned that their comparison may be biased since they used different types of filters in their samplers at the middle and ends of the buildings. In this study, the higher concentrations near the front end of the building were attributed to bigger pigs located in the pens close to the front door. These pigs were better able to withstand the cold draft from the frequent opening of the front door than the smaller pigs. They were also more active and needed more feed, resulting in more dust production in the pens near the front door. The means of the dust mass concentration measured at each sampling location (1, 2, 3, 4, 5, 6, 7, 8, 9, and 10) at cross-section I were compared with the means at the corresponding sampling locations at the other cross-sections (II, III, IV, and V). The results of the comparison of the means are presented in table 2. In December, the means for almost all sampling locations at cross-section I were, in general, higher than the means at cross-sections III to V but not significantly different from those at cross-section II. In addition, the means of the sampling locations at cross-sections III to V were, in general, not significantly different. Thus, if limited sampling locations are desired, then using cross-sections I and III could be sufficient to obtain a reasonable estimate of the average mass concentration in the building.

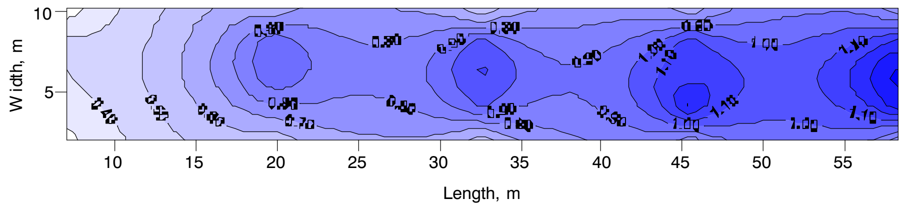
The contours of the spatial distribution of the average mass concentration at 0.8 and 1.6 m elevations for the measurements in June 2006 are shown in figure 10. The building was tunnel-ventilated in June, in which the air entered through the front endwall and exhausted from the building by the fans located on the opposite end. In addition to the air coming from the endwall, the ceiling inlets were also partly open to provide additional ventilation.

The results of pairwise comparison of the means of adjacent sampling locations within each cross-section in June are shown in table 1. As in the means of dust concentration measured in December, the mean dust concentrations among the sampling locations within each cross-section for June were significantly different at the 5% level. At 0.8 m, the mean dust concentration at sampling locations 7, 8, and 9 (over the alley and near the front of the pen) were significantly higher than at sampling locations 6 and 10 (close to the sidewalls). Similarly at 1.6 m, the sampling locations over the alley and near the front of the pen (2, 3, and 4) had significantly higher concentration than the sampling locations near the rear of the pen (1 and 5) except at cross-section I where the means at sampling locations 1 and 2 were not significantly different. Thus, across the length of the building, the dust mass concentration was highest near the central alley or close to the front of the pen and decreased toward the sidewall or rear of the pens. The highest dust concentration near the alley was consistent with the general notion of where the dust is produced and the general air movement. As shown in figure 11, the air from the ceiling inlets traveled across the ceiling and

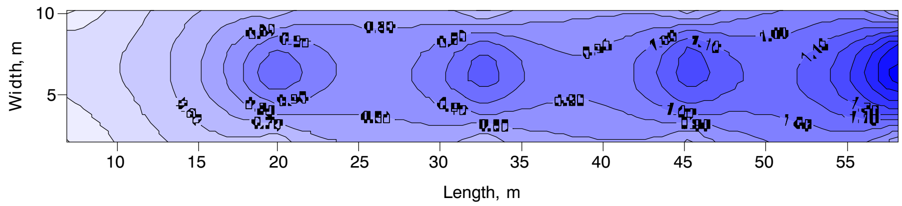
Table 2. Comparison of the means of the TSP mass concentration (mg m^{-3}) at each cross-section at elevations of 0.8 and 1.6 m in December and June.[a]

Elevation and Cross-Section		December 2005, Sampling Location					June 2006, Sampling Location				
		1	2	3	4	5	1	2	3	4	5
1.6 m	I	1.90 a	3.33 a	2.89 a	3.47 a	1.83 a	0.27 c	0.36 d	0.39 d	0.43 d	0.24 d
	II	1.91 a	2.87 ab	2.27 ab	3.04 a	1.57 ab	0.52 b	0.79 c	0.98 c	0.99 c	0.60 b
	III	1.02 b	2.82 ab	1.65 b	2.73 a	1.22 bc	0.53 b	1.01 b	1.11 bc	1.07 bc	0.48 c
	IV	1.48 ab	2.48 ab	2.22 ab	2.89 a	1.57 ab	0.72 a	1.32 a	1.15 b	1.18 ab	0.59 b
	V	1.32 ab	2.31 b	1.89 b	1.69 b	0.86 c	0.74 a	1.34 a	1.43 a	1.24 a	0.71 a
		6	7	8	9	10	6	7	8	9	10
0.8 m	I	2.21 b	3.67 a	2.60 a	3.81 a	1.77 a	0.30 a	0.37 d	0.45 c	0.47 d	0.27 c
	II	2.92 a	3.24 ab	1.94 ab	3.07 a	1.94 a	0.53 c	0.85 c	1.12 b	0.96 c	0.62 ab
	III	2.05 bc	2.79 ab	1.74 b	2.90 a	2.12 a	0.62 bc	0.96 bc	1.18 b	1.06 bc	0.56 b
	IV	1.48 c	2.66 ab	2.24 ab	2.98 a	1.94 a	0.68 ab	1.08 b	1.26 b	1.20 b	0.63 ab
	V	1.79 bc	2.60 b	1.94 ab	1.78 b	1.08 b	0.73 a	1.31 a	1.68 a	1.49 a	0.68 a

[a] Means followed by the same letter within the same column (i.e., sampling location) for each elevation are not significantly different at the 5% level.



(a) 1.6 m



(b) 0.8 m

Figure 10. Spatial distribution of the average TSP mass concentration (mg m^{-3}) measured in June at elevations of (a) 1.6 m and (b) 0.8 m. Data were plotted using Surfer version 7, which uses the weighted average interpolation algorithm.

toward the sidewall. Upon hitting the sidewall, the jet changed direction: part of the air jet flowed toward the floor, part of it moved forward toward the exhaust fans, and the rest of the airflow traveled along the floor and upward toward the front of the pens or close to the central alley, where dust was generated. This airflow pattern resulted in higher dust mass concentration over the alley.

As expected in a tunnel-ventilated building, dust builds up toward the end of the building. Along the length of the building and in both vertical locations (0.8 and 1.6 m from the floor), the dust mass concentration was lowest near the endwall inlet and highest near the opposite end. This dust spatial distribution was the reverse of that in December when the dust mass concentration was higher near the endwall inlet. The dust spatial distribution in June was attributed to the fact that as the air travels from one end of the building, additional particles that get collected in the succeeding samplers are carried along. The means of dust mass concentration at each sampling location (1, 2, 3, 4, 5, 6, 7, 8, 9. 10) at cross-section I were also compared with the mean dust concentration at the corresponding locations in the other cross-sections (II, III, IV, and V). As presented in table 2, significant differences among the means at corresponding locations existed. Although the mean concentrations at the sampling locations in cross-section V were higher than those in the other cross-sections, the differences between the means of cross-sections V and IV were usually not significant. The same observation was also true between IV and III, and between III and II. Thus, when a limited number of sampling locations is required by a study in a tunnel-ventilated building, samplers can be located over the pens and alley in the middle section and near the exhaust fans of the building

Figure 11. Airflow pattern over the pens, visualized with white smoke. The arrow indicates the air movement from the ceiling inlets toward the sidewall: part of it falls, part moves horizontally toward the exhaust side, and part goes back toward the front of the pens.

Differences in Mass Concentration Between Two Vertical Locations

Figures 12 and 13 show comparisons of the average dust mass concentration at elevations of 1.6 and 0.8 m for each cross-section of the building in December and June, respectively. In general, the dust mass concentration was higher at 0.8 m than at 1.6 m. This result was expected because of the proximity of the sampling location at 0.8 m to the dust source on the floor.

A *t*-statistic for two independent samples was performed to test if the differences between the means of samples at 0.8 and 1.6 m were significant at the 5% level. In some of the sample combinations, the assumption of the equality of variance was not valid at the 5% level using an F-test. Thus, in the analysis, an unequal variance method was used in the approximation of the standard errors instead of the pooled variance. Table 3 shows the results of the *t*-test analysis. In December, the means of only three sampling location combinations (II-1 vs. II-6, III-1 vs. III-6, and III-5 vs. III-10) were found to be statistically significant ($p < 0.05$). The common characteristic of these location combinations was that they were over the pen, away from the dust source, and close to the sidewalls. In June, only two location combinations (IV-2 vs. IV-7 and V-4 vs. V-9) had means that were significantly different. In the V-4 vs. V-9 combination, the dust mass concentration at 1.6 m (V-9) was significantly higher than that at 0.8 m (V-4). In general, though, the concentrations at 0.8 and 1.6 m were not significantly different. Contrary to this study, Hinz and Linke (1998), who measured dust concentra–

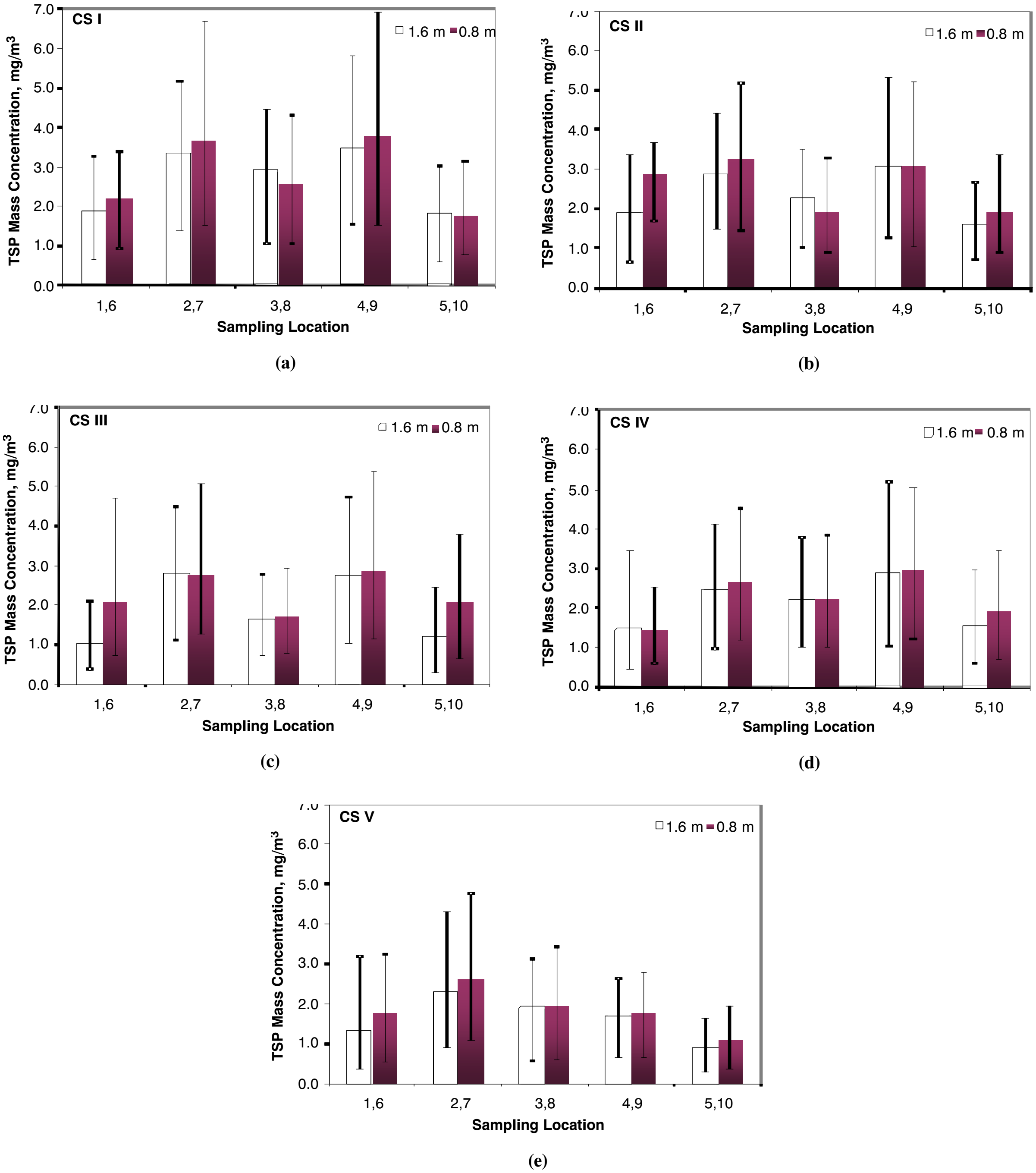


Figure 12. Comparison of the TSP mass concentration in December measured at elevations of 1.6 and 0.8 m at the five cross-sections (CS) in the building: (a) CS I, (b) CS II, (c) CS III, (d) CS IV, and (e) CS V. The plotted values are averages over seven sampling days. The error bars represent the range of measurements.

tions at 1.5 and 2.5 m from the floor of a fattening piggery in Germany, reported no significant differences in dust levels. It should be pointed out that in Hinz and Linke's study, the air was exhausted through the roof, which produced an airflow pattern different from that obtained in this study.

Temporal Variation in TSP Mass Concentration

The average dust mass concentration in the building was higher during daytime than at nighttime in December and June. This result is similar to the findings reported by Hinz and Linke (1998) in which maximum concentrations of 5 and 2 mg m^{-3} were obtained at daytime and nighttime, respectively. Hinz and Linke (1998), who performed their measurements in a fattening piggery in Germany, attributed the difference to the higher activity at daytime than at nighttime. In Kim et al. (2005), higher dust concentrations were obtained in the afternoon than at night in a growing-finishing building in Korea. The higher concentration in the afternoon was due to the higher animal activity level as well. In this study, for the December measurements, the average dust mass concentration in the room during daytime was 226% higher than during nighttime (3.13 vs. 1.38 mg m^{-3}), while

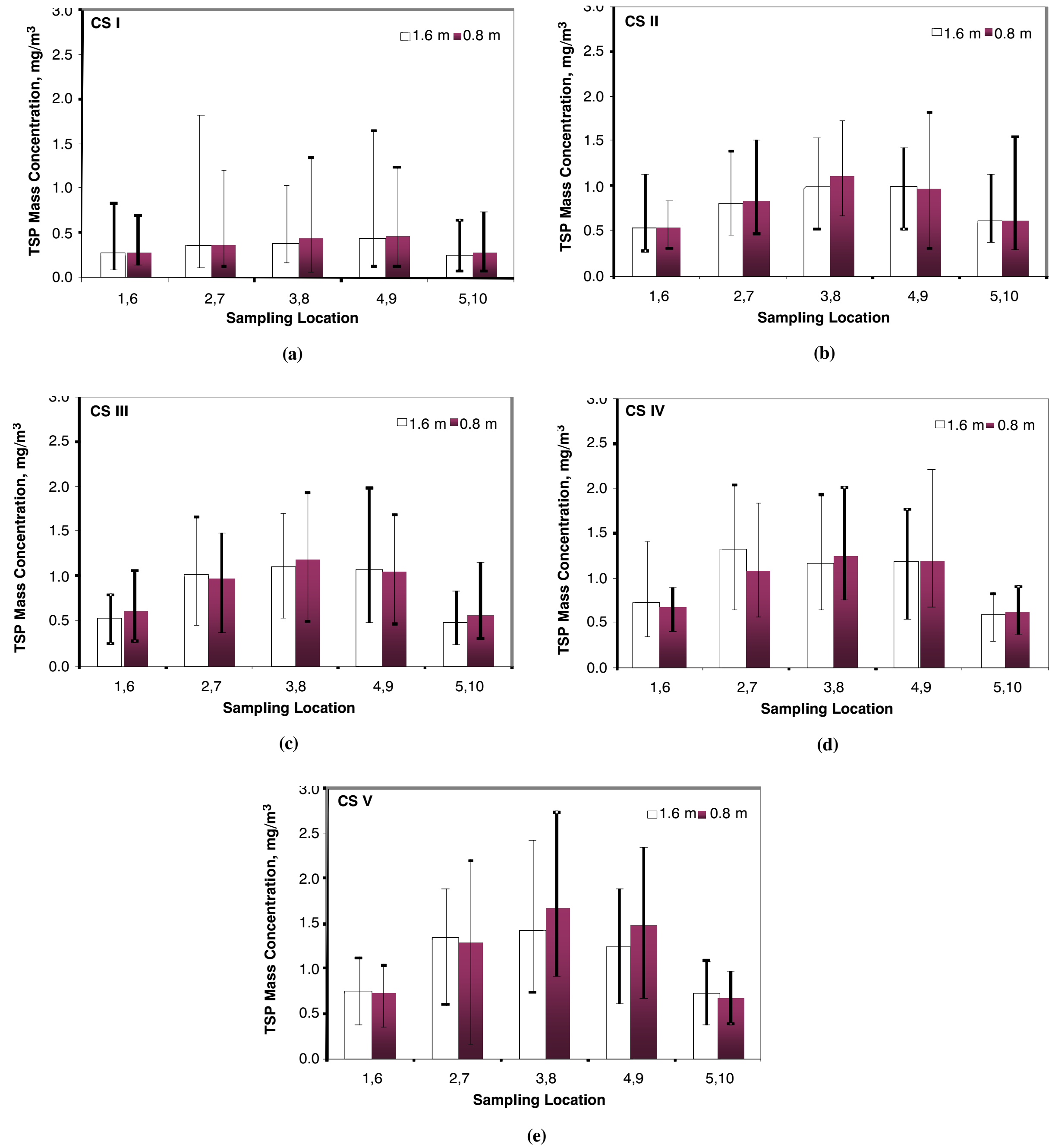


Figure 13. Comparison of the TSP mass concentration in June measured at elevations of 1.6 and 0.8 m at the five cross-sections (CS) in the building: (a) CS I, (b) CS II, (c) CS III, (d) CS IV, and (e) CS V. The plotted values are averages over 15 sampling days. The error bars represent the range of measurements.

the daytime mass concentration in June was 139% higher than at nighttime (0.96 vs. 0.69 mg m^{-3}) (table 4). The daytime average concentration in December ranged from 1.26 to 5.48 mg m^{-3} with CVs ranging from 8.48% to 36.47%. During nighttime, the average dust concentration ranged from 0.45 to 2.75 mg m^{-3} with a higher CV range of 14.78% to 45.28%. In June, the average dust concentration during daytime sampling ranged from 0.26 to 2.01 mg m^{-3} with CVs ranging from 13.55% to 98.24%. The range of average dust mass concentration in June was only from 0.21 to 1.32 mg m^{-3}, and the CVs were from 14.85% to 69%. Higher dust mass concentrations during daytime are expected due to more activity inside the building during the day, i.e., animals are awake and more active, and there is more frequent intervention by the workers to provide feed, check on the condition of the sick pigs, and relocate pigs to other pens or buildings. Higher CVs in June than in December indicate greater day-to-day variation in dust concentration, which could be attributed to the diurnal change in building ventilation rate, as shown in figure 7.

Table 4 shows the results of the paired comparison of the mean TSP mass concentration at daytime and nighttime. In December, the mean dust mass concentrations at daytime were all significantly different from those of the nighttime samples. In addition, the difference between the mean daytime and nighttime dust mass concentrations ranged from

Table 3. Paired comparison of the TSP mass concentrations ($mg\ m^{-3}$) at elevations of 0.8 and 1.6 m.[a]

Sampling Location 1.6 m (x_1)	0.8 m (x_2)	December 2005 d (x_1 - x_2)	SE	t[b]	June 2006 d (x_1 - x_2)	SE	t[c]
I-1	I-6	-0.31	0.33	-0.94	-0.03	0.04	-0.7
I-2	I-7	-0.34	0.57	-0.59	-0.02	0.07	-0.25
I-3	I-8	0.29	0.44	0.66	-0.06	0.07	0.07
I-4	I-9	-0.33	0.66	-0.51	-0.03	0.08	-0.4
I-5	I-10	0.06	0.32	0.18	-0.04	0.04	-0.98
II-1	II-6	-1.01	0.29	-3.54*	-0.01	0.05	-0.15
II-2	II-7	-0.37	0.51	-0.73	-0.06	0.07	-0.88
II-3	II-8	0.33	0.3	1.09	-0.14	0.07	-1.88
II-4	II-9	-0.03	0.55	-0.05	0.03	0.09	0.31
II-5	II-10	-0.37	0.29	-1.27	-0.02	0.06	-0.31
III-1	III-6	-1.02	0.32	-3.17*	-0.09	0.04	-1.92
III-2	III-7	0.03	0.49	1.31	0.05	0.08	0.6
III-3	III-8	-0.09	0.26	-0.34	-0.07	0.09	-0.75
III-4	III-9	-0.17	0.49	-0.34	0.01	0.08	0.09
III-5	III-10	-0.9	0.32	-2.81*	-0.08	0.04	-1.69
IV-1	IV-6	0	0.31	-0.01	0.05	0.05	1.01
IV-2	IV-7	-0.18	0.46	-0.4	0.24	0.1	2.42*
IV-3	IV-8	-0.01	0.4	-0.03	-0.11	0.09	-1.14
IV-4	IV-9	-0.09	0.56	-0.16	-0.02	0.09	-0.22
IV-5	IV-10	-0.38	0.35	-1.08	-0.04	0.04	-1.04
V-1	V-6	-0.47	0.31	-1.52	0.01	0.05	0.17
V-2	VI-7	-0.29	0.46	-0.63	0.02	0.12	0.18
V-3	V-8	-0.05	0.36	-0.13	-0.24	0.13	-1.84
V-4	VI-9	-0.09	0.32	-0.28	-0.25	0.11	-2.34*
V-5	VI-10	-0.23	0.19	-1.17	0.03	0.05	0.77

[a] SE = standard error of the difference between the means. Asterisks (*) indicate means that are significantly different at the 5% level.
[b] $t_{critical}$ = 2.06 (5% level, df = 26).
[c] $t_{critical}$ = 2.00 (5% level, df = 58).

1.27 to 2.08 $mg\ m^{-3}$. In June, the results were mixed; for five out of 15 days, the differences between the means of daytime and nighttime samples were not significant. Further, the differences between the means in June ranged only from 0.06 to 0.53 $mg\ m^{-3}$. Thus, to minimize the effect of the difference in daytime and nighttime mass concentration, the sampling period should be at least one day instead of 12 h.

Figures 14 and 15 show a comparison of the contours of the dust mass concentration during the daytime and nighttime sampling periods in December and June, respectively. As mentioned previously, the daytime concentrations were higher than the nighttime concentrations. The contours of the spatial distribution of the daytime and nighttime concentrations, however, appear similar for both December and June. Similar to figure 9, the mass concentrations during the daytime and nighttime sampling periods in December were highest near the midsection of the pens (at widths of about 4 and 8 m) and near the central alley (at a width of about 6 m) due to the proximity of these locations to the feeding tanks and feeding mats. The contours of the spatial distribution of dust mass concentration for both daytime and nighttime in June (fig. 15) are also similar to those in figure 9, in which the dust mass concentration for both daytime and nighttime sampling was lowest close to the front of the building and increased toward the exhaust side of the building. Across the length of the building, the mass concentration was highest over the central alley due to the location of the dust source and the prevailing air movement in the building.

Table 4. Paired-comparison of the daytime and nighttime total suspended particulate matter mass concentrations ($mg\ m^{-3}$) per day.[a]

Day	Mean Day (x_1)	Mean Night (x_2)	d (x_1 - x_2)	SE_d	t[b]
December 2005					
1	2.86	0.97	1.89	0.14	13.06
2	2.74	1.13	1.61	0.17	9.62
3	2.45	1.18	1.27	0.13	10.09
4	3.25	1.51	1.74	0.17	10.21
5	3.55	1.48	2.08	0.17	12.14
6	3.38	1.41	1.96	0.18	10.83
7	3.71	1.97	1.74	0.2	8.77
Avg.	3.13	1.38			
June 2006					
1	1.19	0.81	0.38	0.07	5.71
2	0.87	0.62	0.24	0.06	3.92
3	1.12	0.65	0.47	0.09	5.48
4	0.95	0.67	0.28	0.09	3.06
5	0.97	0.68	0.29	0.08	3.77
6	1.1	0.97	0.13	0.09	1.42*
7	1.2	0.67	0.53	0.1	5.25
8	0.63	0.55	0.07	0.06	1.22*
9	0.81	0.64	0.17	0.09	1.87*
10	0.97	0.68	0.28	0.1	2.65
11	1.02	0.83	0.19	0.1	1.87*
12	0.99	0.66	0.33	0.1	3.35
13	0.94	0.67	0.27	0.09	3.08
14	0.64	0.57	0.06	0.06	1.06*
15	1.03	0.73	0.29	0.11	2.59
Avg.	0.96	0.69			

[a] SE_d = standard error of *d* or the difference between means of x_1 and x_2. Asterisks (*) indicate means of day and night samples that are not significantly different at the 5% level.
[b] *t* = 1.99 to 2.00 (5% level, df = 63 to 72) for December; *t* = 1.98 to 2.00 (5% level, df = 59 to 96) for June.

Spatial Variability of NH_3 Concentration

Variation Along and Across Building Length

The volumetric concentrations of ammonia (NH_3) averaged over five sampling days in both December and June are presented by sampling location in table 5. Averaged over all five sampling days and over all 30 sampling locations, the concentration in the building in December was almost eight times as much as the average concentration in June (9.55 vs. 1.20 ppm). By sampling location, the mean NH_3 concentration ranged from 5.74 to 12.72 ppm in December, while it was between 0.76 and 3.08 ppm in June. These average concentrations are still below the American Conferences of Governmental Industrial Hygienists (ACGIH) threshold limit value (TLV) of 25 ppm (ACGIH, 2011). The ratio of the average concentration in December to that in June ranged from 3.95 to 13.76, with the highest concentration ratio occurring in the longitudinal midsection of the building (cross-section III). The coefficient of variation (CV) ranged from 14.91% to 53.44% in December. In June, there was higher variability among the sampling locations, with CVs ranging from 45.49% to 130.44%. Similar to the TSP mass concentration, the higher CVs per sampling location in June could be attributed to the variable building ventilation rate. Thus, more sampling days would be required in June than in December in order to get a more reasonable estimate of the NH_3 concentration in the building.

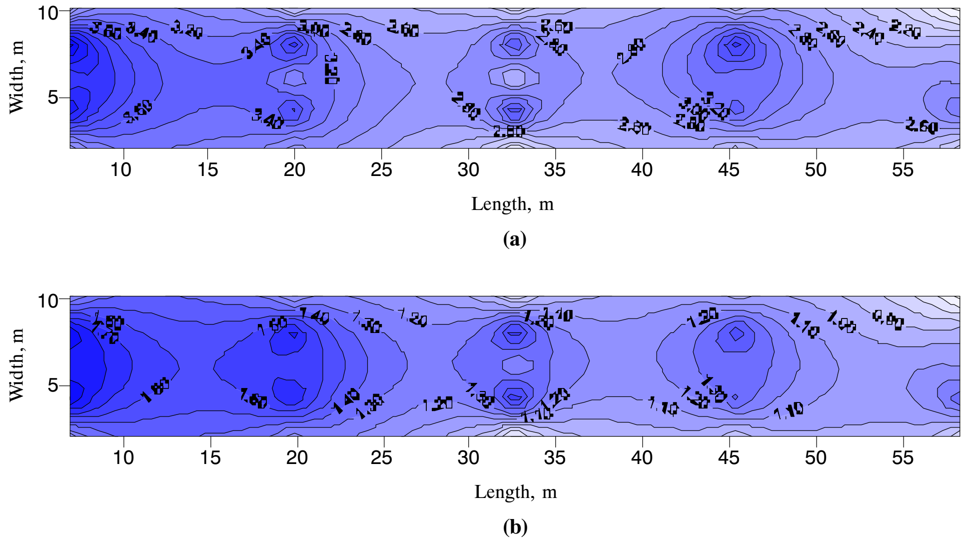


Figure 14. Spatial distribution of the average TSP mass concentration (mg m^{-3}) at 1.6 m from the floor during (a) daytime and (b) nighttime sampling in December. Data were plotted using Surfer version 7, which uses the weighted average interpolation algorithm.

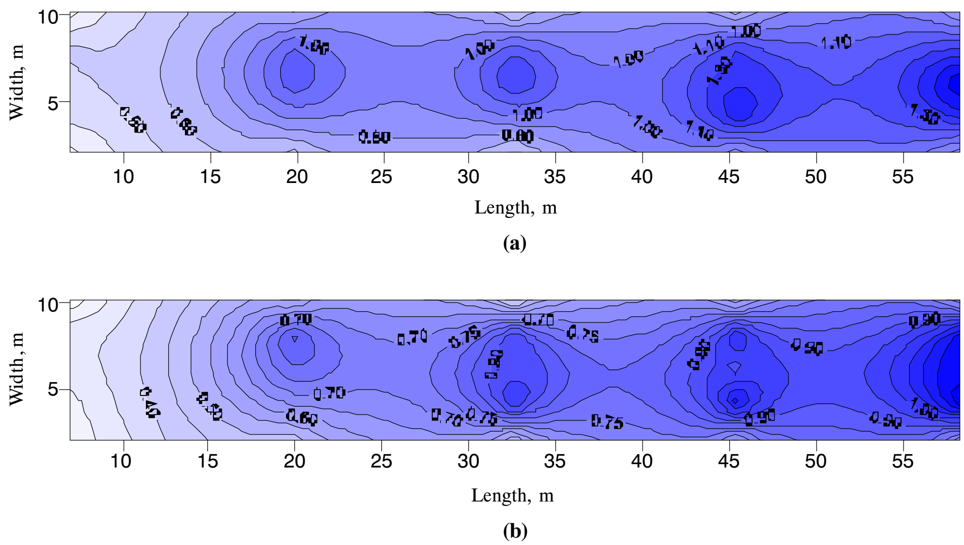


Figure 15. Spatial distribution of the average TSP mass concentration (mg m^{-3}) at 1.6 m from the floor during (a) daytime and (b) nighttime sampling in June. Data were plotted using Surfer version 7, which uses the weighted average interpolation algorithm.

Figure 16 shows the contours of NH_3 concentration at 1.6 and 0.8 m from the floor for the measurements in December. The spatial distributions at both elevations appear to be similar. In addition, the NH_3 concentration was almost symmetrical with respect to the longitudinal midsection (alley, width = 6 m) of the building. At the building length of about 33 m, the concentration was lowest over the alley, while it increased toward the sidewall regions. The highest concentrations near the sidewalls were expected, since the floors near the sidewalls were always wet with urine and feces that favor NH_3 volatilization. Along the length of the building, the concentration was lowest close to the front door (north end in fig. 2) and gradually increased toward the opposite end. The increasing concentration from the front toward the end section of the building can be attributed to the accumulation of NH_3 concentration toward the exhaust side of the building. Even when the pit fans were operating, the capacity of these fans was not enough to pull the air down through the manure pit. This was evident when a smoke detector was used to visualize the movement of air; the smoke settled on the floor and did not go through the slots. The higher concentration toward the exhaust side of the building can also be partly attributed to the condition of the floor. By visual inspection, the floor closer to the exhaust fans was more littered with feces and more wet due to urine.

With the sampling locations at cross-section I considered as the reference, the relative concentrations of NH_3 at the corresponding locations at cross-sections III and V were determined and are presented in table 6. If the values at cross-sections III and V were below 1, the concentration at cross-section I was higher than that in either cross-section III or V. As shown in table 5, the concentration away from the front of the building was higher by as much as 222% over the alley in cross-section V, sampling location 8. Over the pen, the concentration at cross-section V was higher by as much as 68%. The differences between the means of each sampling location within each cross-section were, in general, not significant at the 5% level. Thus, in December, the variation

Table 5. Ammonia concentration (ppm) per sampling location.

Sampling Location	December 2005				June 2006				Dec./June Ratio[a]
	Average	CV (%)	Maximum	Minimum	Average	CV (%)	Maximum	Minimum	
I-1	8.13	28.12	11.60	5.92	1.12	54.02	1.91	0.40	7.2
I-2	7.54	33.82	11.81	5.56	1.10	59.94	1.99	0.50	6.8
I-3	6.72	15.29	8.47	5.87	1.24	59.94	2.28	0.45	5.4
I-4	7.73	26.69	11.26	5.97	1.12	65.39	2.18	0.30	6.9
I-5	7.90	27.79	11.60	5.94	0.92	66.45	1.78	0.22	8.6
I-6	7.51	32.66	11.38	5.24	1.24	53.54	1.97	0.43	6.1
I-7	7.05	36.42	10.96	4.73	1.15	58.00	2.00	0.50	6.1
I-8	5.74	16.17	6.92	4.79	1.45	50.87	2.35	0.51	4.0
I-9	7.75	25.16	11.16	6.28	1.15	64.23	2.24	0.50	6.8
I-10	7.61	21.69	10.23	5.95	1.01	61.84	1.88	0.41	7.6
III-1	10.17	22.86	13.59	7.83	0.76	72.96	1.42	0.17	13.3
III-2	10.72	21.17	13.27	8.99	0.95	74.09	1.94	0.41	11.3
III-3	6.54	23.38	8.49	4.57	1.22	57.44	2.03	0.46	5.4
III-4	11.08	22.41	14.35	8.95	0.81	58.55	1.45	0.41	13.8
III-5	11.44	23.15	15.25	9.09	0.84	56.23	1.35	0.33	13.7
III-6	9.55	24.35	12.54	6.72	0.77	64.16	1.47	0.36	12.3
III-7	10.97	19.66	13.50	8.81	1.04	92.01	2.57	0.31	10.5
III-8	8.83	14.91	10.93	7.81	1.44	50.87	2.39	0.58	6.1
III-9	10.51	23.17	14.57	8.87	0.99	45.49	1.53	0.52	10.6
III-10	10.20	28.34	14.39	7.45	0.85	81.36	1.83	0.25	12.0
V-1	12.09	26.79	16.78	8.96	1.08	109.97	2.55	0.08	11.2
V-2	12.44	28.59	17.02	7.77	1.09	106.90	2.75	0.12	11.5
V-3	12.29	53.44	23.40	7.49	2.04	76.36	4.00	0.27	6.0
V-4	10.23	43.73	18.02	7.17	1.31	85.92	2.55	0.16	7.8
V-5	11.14	42.56	17.70	6.70	1.23	73.61	2.10	0.22	9.1
V-6	11.06	16.83	13.12	9.21	1.27	92.54	3.01	0.19	8.7
V-7	11.83	20.77	14.52	8.54	1.03	130.44	3.25	0.00	11.5
V-8	12.72	40.33	19.78	7.57	3.08	67.09	5.31	0.49	4.1
V-9	9.98	41.00	17.01	6.91	1.22	93.62	2.54	0.11	8.2
V-10	9.15	38.04	13.71	5.69	1.35	60.61	2.17	0.13	6.8
Average	9.55				1.20				

[a] Based on average concentration.

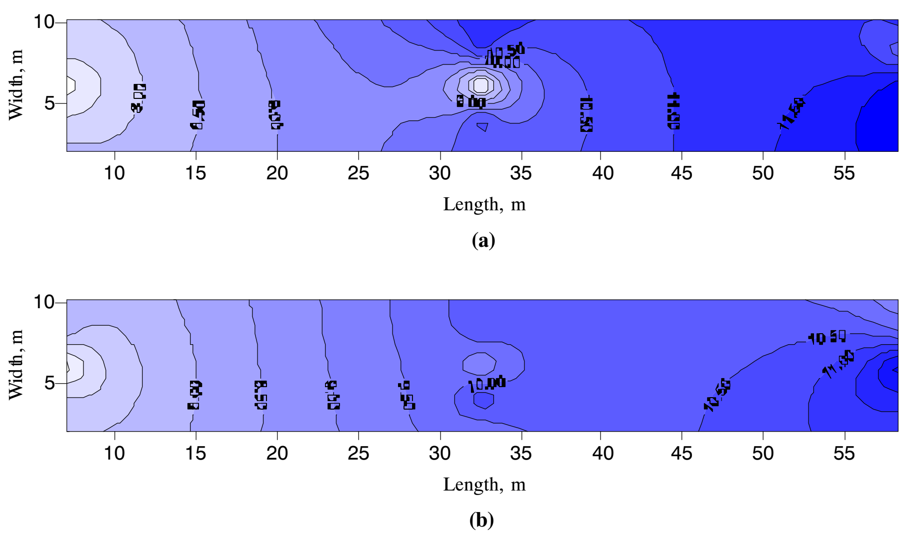


Figure 16. Spatial distribution of the average NH_3 concentration (ppm) in December at elevations of (a) 1.6 m and (b) 0.8 m. Data were plotted using Surfer version 7, which uses the weighted average interpolation algorithm.

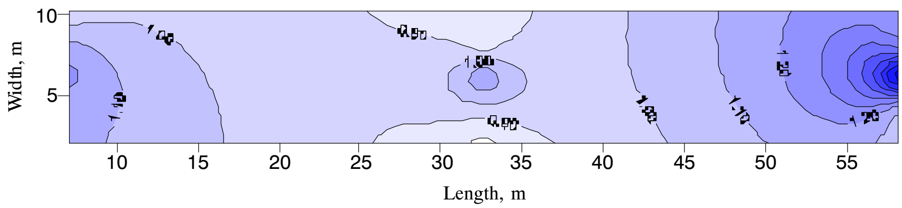
along the length of the building was higher than the variation across the building such that if a limited number of sampling locations is needed, then NH_3 can be measured either over the alley or over the pen. Instead of distributing the sampling locations across the building, more locations should be sampled along the length of the building.

Figure 17 shows the spatial variation of NH_3 concentration across and along the length of the building in June. The spatial concentration inside the building was almost uniform. Contrary to the spatial distribution in December, the concentration over the alley and near the front of the pens was slightly higher than the concentration over the pens. The

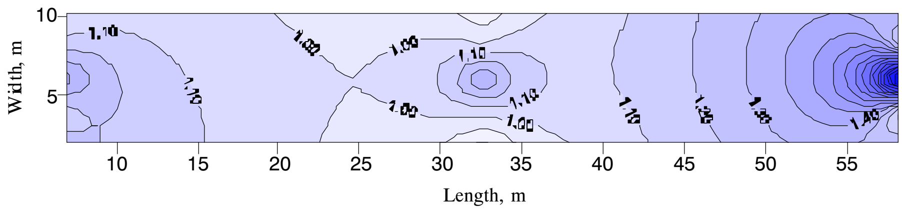
Table 6. Ratios of ammonia concentrations in each sampling location over the reference locations in December.

Sampling Location	Cross-Section I		Cross-Section III		Cross-Section V	
	Within[a]	Between[b]	Within[a]	Between[b]	Within[a]	Between[b]
1	1.21	1	1.55	1.25	0.98	1.49
2	1.12	1	1.64	1.42	1.01	1.65
3	1	1	1	0.97	1	1.83
4	1.15	1	1.69	1.43	0.83	1.32
5	1.18	1	1.75	1.45	0.91	1.41
6	1.31	1	1.08	1.27	0.87	1.47
7	1.23	1	1.24	1.56	0.93	1.68
8	1	1	1	1.54	1	2.22
9	1.35	1	1.19	1.36	0.78	1.29
10	1.33	1	1.16	1.34	0.72	1.20

[a] The reference is the concentration at the alley within each cross-section (sampling locations 3 and 8).
[b] The reference is cross-section I.



(a)



(b)

Figure 17. Spatial distribution of the average NH_3 concentration (ppm) in June at elevations of (a) 1.6 m and (b) 0.8 m. Data were plotted using Surfer version 7, which uses the weighted average interpolation algorithm.

lower concentration over the pens compared to that over the alley can be attributed to the air velocity distribution in the building. As shown in figure 8c, the air velocity over the alley was lower than that over the pens, especially from the longitudinal midsection to the exhaust side of the building. The lower air velocity over the alley was due to the presence of the front door and the absence of an exhaust fan at the other end of the alley.

The variability across the length of the building in figure 17 was more pronounced at cross-section V. Table 7 shows the concentrations over the pens relative to the concentration over the alley. The concentration over the pens was lower by as much as 67% at cross-section V. At the lower elevation (fig. 17b), the concentration across the length of the building was more variable, especially near the end or exhaust section of the building. The differences among the means of the sampling locations within each cross-section were not significant at the 5% level except in cross-section V. Table 7 also shows a comparison of the concentrations at individual sampling locations between cross-section I (the reference) and cross-sections III and V. The concentration over the alley at cross-section V was higher by as much as 212% than that at cross-section I. The concentrations over the front end of the pens (locations 2, 4, 7, and 9) at cross-sections I and V were almost similar. These results indicated that for a tunnel-ventilated building during summer, the representative concentration of NH_3 should be measured over the pen and alley, and preferably close to the exhaust side of the building or where the floor is more littered with feces and urine, to determine the maximum concentration. When sampling NH_3 near the exhaust, however, the positive bias due to NH_3 that could flow out of the manure pit, due to the negative pressure created by the exhaust fan, should be accounted for in the measured concentration.

Along the length of the building, the concentration was nearly uniform, varying only by as much as 0.40 ppm. This result is similar to the results reported by Hinz and Linke (1998), in which no great variation in NH_3 was measured along the length of a fattening piggery monitored in Germany. However, Hinz and Linke (1998) reported NH_3 concentrations ranging from 10 to 25 ppm. In this study, although the concentrations were nearly uniform throughout the building, high concentrations were measured near the exhaust side of the building (fig. 17). It should be noted, however, that the exhaust fans were about 7 m away from the sampling location shown in figure 17. This high concentration near the exhaust could be attributed to the accumulation of NH_3 due to the absence of an exhaust fan to directly ventilate the central alley. The average NH_3 concentration measured directly in front of the exhaust fans, which is not plotted in figure 17, was

Table 7. Ratios of ammonia concentrations in each sampling location over the reference locations in June.

Sampling Location	Cross-Section I		Cross-Section III		Cross-Section V	
	Within[a]	Between[b]	Within[a]	Between[b]	Within[a]	Between[b]
1	0.91	1	0.63	0.68	0.53	0.96
2	0.89	1	0.77	0.86	0.53	0.99
3	1	1	1	0.99	1	1.65
4	0.90	1	0.66	0.72	0.64	1.17
5	0.74	1	0.68	0.91	0.60	1.34
6	0.85	1	0.54	0.63	0.41	1.03
7	0.79	1	0.72	0.91	0.33	0.90
8	1	1	1	0.99	1	2.12
9	0.79	1	0.69	0.87	0.40	1.07
10	0.69	1	0.59	0.84	0.44	1.35

[a] The reference is the concentration at the alley within each cross-section (sampling locations 3 and 8).
[b] The reference is cross-section I.

2.7 ppm; this concentration was significantly higher than those shown in figure 17. The higher concentration in front of the exhaust fan could be due to NH_3 that flowed from the manure pit. The NH_3 from the pit could have introduced positive bias to the measured concentration at the exhaust.

Vertical Variation in Ammonia Concentration

Figure 18 shows a comparison of the concentration of NH_3 averaged over five sampling days in December and measured at elevations of 0.8 and 1.6 m. At cross-section I, the concentration at 1.6 m was either equal to or higher than the concentration at 0.8 m, but the difference between the means was not significant at the 5% level. At cross-section sections III and V, the results were mixed: in cross-section III, the concentration at 1.6 m was higher than at 0.8 m in three sampling location combinations, while in cross-section V, the concentration at 0.8 m was higher than at 1.6 m in only one sampling location combination (3 vs. 8) (alley). In all but one location combination (3 vs. 8) in cross-section III, the mean NH_3 concentrations at 1.6 and 0.8 m were not significantly different at the 5% level.

Figure 19 shows a comparison of the average concentration at elevations of 1.6 and 0.8 m in June. In all but two sampling location combinations (2 vs. 7 and 4 vs. 9 in cross-section V), the concentration at 0.8 m was higher than

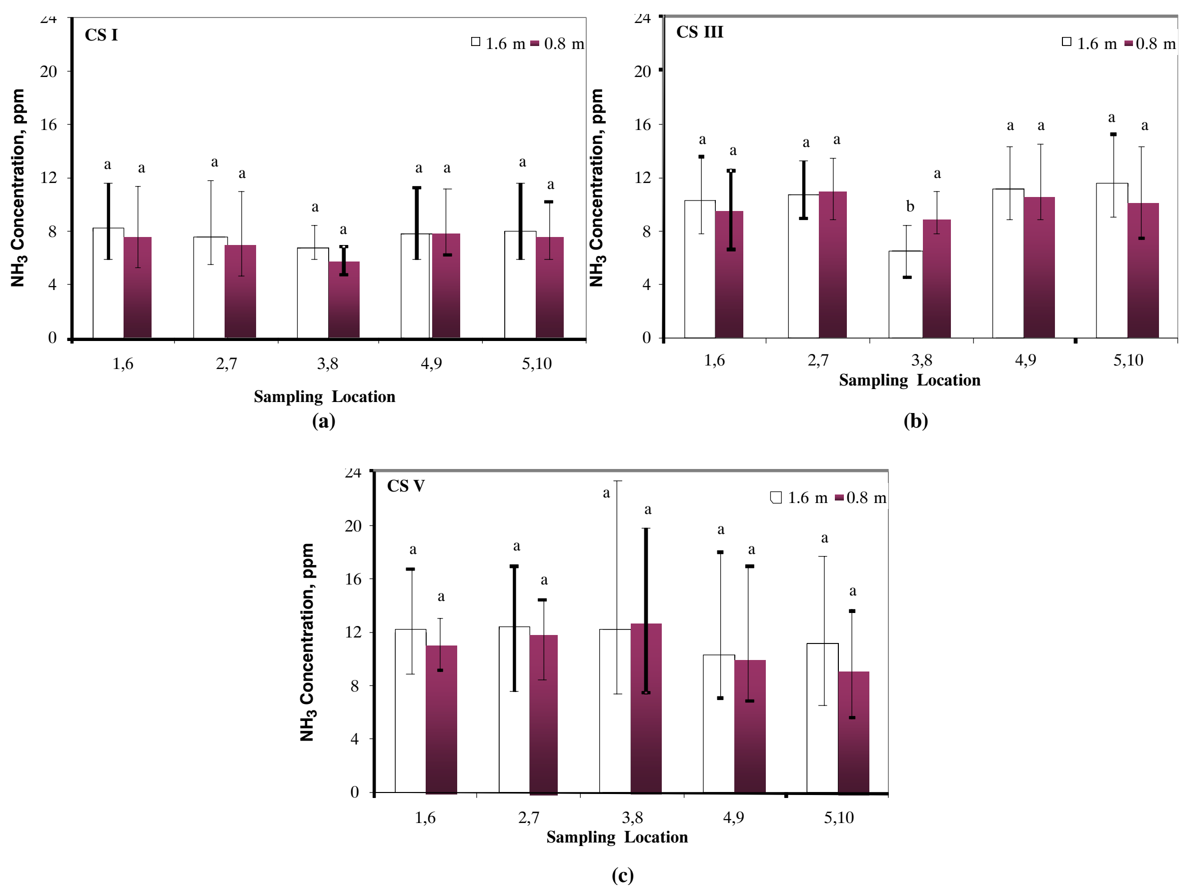


Figure 18. Comparison of NH_3 concentration in December measured at elevations of 1.6 and 0.8 m at three cross-sections (CS) in the building: (a) CS I, (b) CS III, and (c) CS V. The plotted values are averages over five sampling days. The error bars represent the range of measurements. Means with the same letter within each elevation are not significantly different at the 5% level.

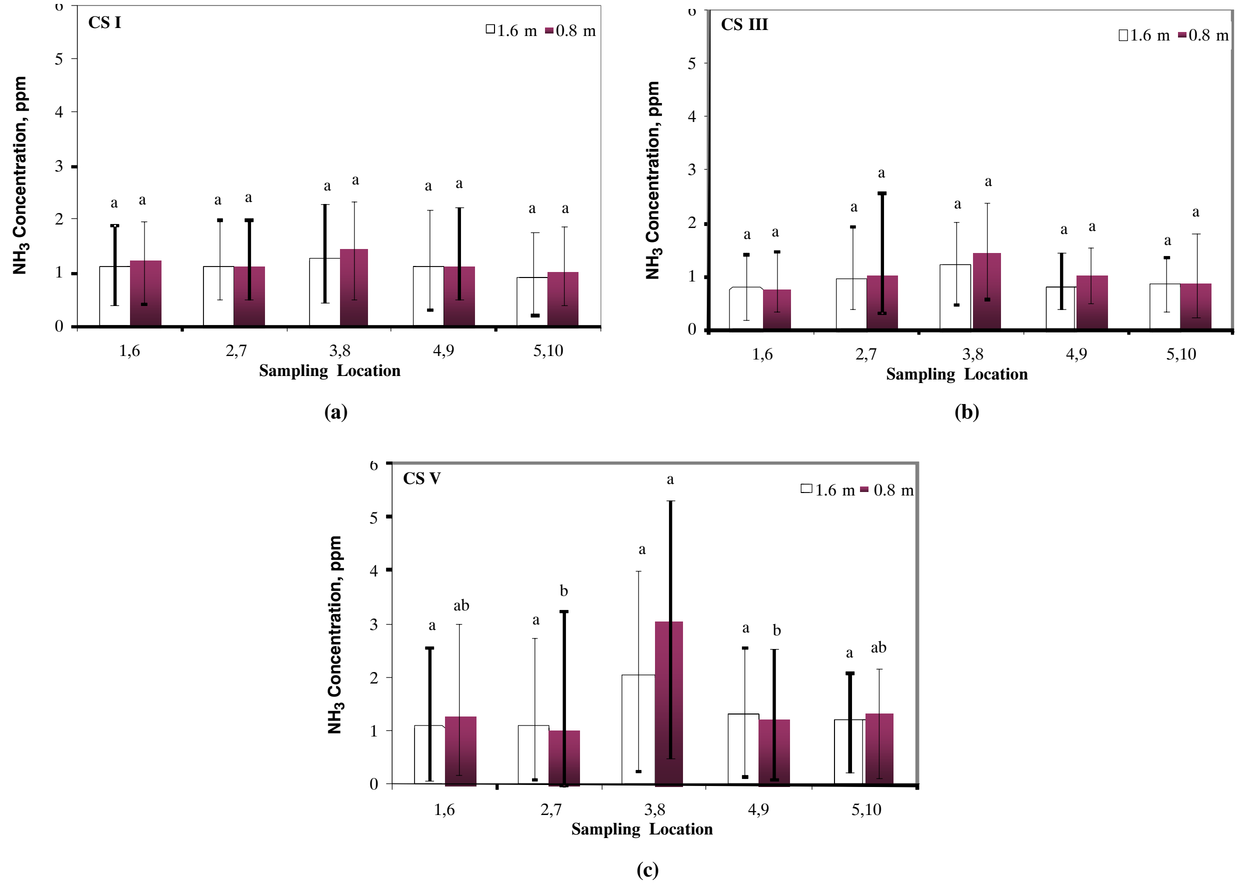


Figure 19. Comparison of NH_3 concentration in June measured at elevations of 1.6 and 0.8 m at three cross-sections (CS) in the building: (a) CS I, (b) CS III, and (c) CS V. The plotted values are averages over five sampling days. The error bars represent the range of measurements. Means with the same letter within each elevation are not significantly different at the 5% level.

that at 1.6 m. However, the differences between the means of locations at elevations of 0.8 and 1.6 m were not significantly different at the 5% level. The results of the comparison of the means at 0.8 and 1.6 m suggest that, in general, the vertical concentration of NH_3 was uniform. Therefore, when measuring the concentration of NH_3 or other light gaseous pollutants inside a building, the vertical location of the sampler will not significantly affect the measured concentration except when the sampling locations are close to the exhaust side of the building.

Temporal Variation in Ammonia Concentration

The concentration of NH_3 averaged over all sampling locations per sampling day is presented in table 8. The overall average concentration in the building in December was almost eight times greater than the average concentration in June (9.55 vs. 1.2 ppm). The average daily concentration in December was between 7.39 and 11.33 ppm. In June, the daily average concentration ranged from 0.50 to 1.90 ppm. The range of CV in December was lower than that in June, ranging from 17.40% to 14.45% as compared 37.95% to 91.11%. Table 8 also shows a comparison of the daily means. In both December and June, the means were significantly different from each other at the 5% level. The lower CV per day in December indicates that obtaining a reasonable estimate of NH_3 concentration in the building in December would require fewer days than in June. Finally, table 8 shows the corresponding building ventilation rates (Q_b) during the measurement of NH_3 concentration. In December, the correlation between the ventilation rate and the daily NH_3 concentration was close to zero. In June, there was a weak negative correlation between the ventilation rate and concentration with a correlation coefficient (R^2) of 0.36. Thus, it is possible that when the building ventilation rate is high, the average NH_3 concentration in the building could be low.

Table 8. Average daily NH_3 concentration (ppm) and the corresponding building ventilation rate (Q_b) in December and June.

	December 2005			June 2006		
Day	Avg.[a] (ppm)	CV (%)	Q_b (m^3 s^{-1})	Avg.[a] (ppm)	CV (%)	Q_b (m^3 s^{-1})
1	11.22 a	18.44	0.78	0.50 c	60.17	46.79
2	11.33 a	42.45	0.76	0.91 b	91.11	41.51
3	7.82 b	17.40	2.00	1.84 a	37.95	45.86
4	7.39 b	22.60	3.65	1.90 a	55.62	46.35
5	10.35 a	31.26	3.66	0.84 bc	78.80	46.88
Avg.	9.55			1.20		

[a] Means followed by the same letter within each column are not significantly different at the 5% level.

Conclusions

The average TSP mass concentration in the building ranged from 0.86 to 3.81 mg m^{-3} in December and from 0.24 to 1.68 mg m^{-3} in June. The spatial gradient of the mass concentration across the length of the building was more pronounced in December than the gradient along the length of the building. In June, the gradient along the length of the building was more pronounced than in December, resulting in essentially uniform concentration in a cross-section.

Knowledge on the spatial gradient of the TSP mass concentration is important when a limited number of sampling locations is desired. During winter or when fresh air enters through the ceiling inlets, the samplers should be distributed crosswise within the building, since the mass concentration is more likely to vary over the pens and alley. During summer or when the building is tunnel-ventilated, the samplers should be distributed lengthwise within the building.

The spatial distribution of the TSP mass concentration in both winter and summer was essentially symmetrical about the longitudinal section of the building. Therefore, the sampler locations could be concentrated on half of the longitudinal section of the building.

The vertical gradient of the TSP mass concentration did not vary significantly, and samplers could be located in either the animal breathing zone (0.8 m elevation) or the human breathing zone (1.6 m elevation).

The difference between daytime and nighttime TSP mass concentration was significant, with the daytime concentration higher than the nighttime concentration due to more activities in the building during daytime. Therefore, the sampling period should be at least 24 h.

The spatial gradient of NH_3 concentration was more pronounced along the length of the building during winter (or when fresh air entered through the ceiling inlets), suggesting that the sampling locations should be distributed lengthwise. During summer (or when the building was tunnel-ventilated), the NH_3 concentration was almost uniform except close to the exhaust side of the building and over the alley, suggesting that if the maximum concentration is desired, then the sampling locations could be concentrated in this cross-section or where the floor is more littered with urine and feces. It should be noted that measuring the concentration upstream of the exhaust fan could be affected by NH_3 coming from the manure pit.

There was a weak negative correlation between the building ventilation rate and the NH_3 concentration, essentially confirming the general notion that the average concentration of NH_3 in the building could be decreased by increasing the building ventilation rate.

Acknowledgements

The authors would like to acknowledge the help with the data collection provided by Jingwei Su, Research Engineer, Department of Agricultural and Biological Engineering, University of Illinois at Urbana-Champaign.

References

ACGIH. 2011. *Threshold Limit Values for Chemical Substances and Physical Agents and Biological Exposure Indices.* Cincinnati, Ohio: American Conferences of Governmental Industrial Hygienists.

Achutan, C., Z. E. Nelson, A. W. Karsten, and P. T. O'Shaughnessy. 2001. Temporal variation in swine confinement indoor air quality. In *Livestock Environment IV*, 579-586. R. R. Stowell, R. Bucklin, and R. W. Bottcher, eds. St. Joseph, Mich.: ASABE.

Barber, E. M., J. R. Dawson, V. A. Battams, and R. A. C. Nicol. 1991. Spatial variability of airborne and settled dust in a piggery. *J. Agric. Eng. Res.* 5: 107-127.

Brockmann, J. E. 2001. Sampling and transport of aerosols. In *Aerosol Measurement: Principles, Techniques, and Applications*, 143-195. P. A. Baron and K. Willeke, eds. New York, N.Y.: John Wiley and Sons.

Conceicao, M. A. P., H. E. Johnson, and C. M. Wathes. 1989. Air hygiene in a pullet house: Spatial homogeneity of aerial pollutants. *British Poultry Sci.* 30(4): 765-776.

Heber, A. J., T. T. Lim, P. C. Tao, and J.-Q. Ni. 2004. Control of air emissions from swine finishing buildings flushed with recycled lagoon effluent. ASAE Paper No. 044156. St. Joseph, Mich.: ASAE.

Hinz, T., and S. Linke. 1998. A comprehensive experimental study of aerial pollutants in and emission from livestock buildings: Part 2. Results. *J. Agric. Eng. Res.* 70: 119-129.

Jerez, S. B., Y. Zhang, J. W. McClure, L. Jacobson, A. J. Heber, S. Hoff, Koziel, and D. Beasley. 2006. Comparison of measured total suspended particulate matter concentrations using tapered element oscillating microbalance and a total suspended particulate sampler. *J. Air and Waste Mgmt. Assoc.* 56(3): 261-270.

Kim, K. Y., H. J. Ko, K. J. Lee, J. B. Park, and C. N. Kim. 2005. Temporal and spatial distributions of aerial contaminants in an enclosed pig building in winter. *Environ. Res.* 99(2): 150-157.

Maghirang, R. G., M. C. Puma, Y. Liu, and P. Clark. 1997. Dust concentrations and particle size distribution in an enclosed swine nursery. *Trans. ASAE* 40(3): 749-754.

Predicala, B. Z., R. G. Maghirang, S. B. Jerez, J. E. Urban, and R. D. Goodband. 2001. Dust and bioaerosol concentrations in two swine finishing buildings in Kansas. *Trans. ASAE* 44(5): 1291-1298.

SAS. 2008. *SAS/ETS User's Guide.* Ver 9.2. Cary, N.C.: SAS Institute, Inc.

Wang, X. 2000. Measurement and modeling of spatial distribution of particulate matter in indoor environments. PhD diss. Urbana, Ill.: University of Illinois at Urbana-Champaign, Department of Agricultural Engineering.

Wang, X., and Y. Zhang. 1999. Development of a critical airflow venturi for air sampling. *J. Agric. Eng. Res.* 73: 257-264.

Wang, X., Y. Zhang, G. L. Riskowski, and M. Ellis. 2002. Measurement and analysis of dust spatial distribution in a mechanically ventilated pig building. *Biosystems Eng.* 81(2): 225-236.

Zhang, Y. 2005. *Indoor Air Quality Engineering*. Boca Raton, Fla.: CRC Press.

Zhang, Y., L. Nijssen, E. M. Barber, J. J. R. Feddes, and M. Sheridan. 1994. Sprinkling mineral oil to reduce dust in pig buildings. *Trans. ASHRAE* 100(2): 1043-1052.

Zhang, Y., G. L. Riskowski, and L. L. Christianson. 1998. Analysis and development of a uniflow aerodynamic deduster. Research report. Atlanta, Ga.: ASHRAE.