Temporal Variation of Indoor Air Quality in an Enclosed Swine Confinement Building

P. T. O'Shaughnessy, C. Achutan, A. W. Karsten

Abstract

Human health hazards can exist in swine confinement buildings due to poor indoor air quality (IAQ). During this study, airborne dust and ammonia concentrations were monitored within a working farrowing facility as indicators of IAQ. The purposes of this study were to assess the temporal variability of the airborne dust and ammonia levels over both a daily and seasonal basis, and to determine the accuracy of real–time sensors relative to actively sampled data. An ammonia sensor, aerosol photometer, indoor relative humidity sensor, and datalogger containing an indoor temperature sensor were mounted on a board 180 cm above the floor in the center of a room in the facility. Sensor readings were taken once every 4 minutes during animal occupancy (3–week intervals). Measurements of total and respirable dust concentrations by standard method, aerosol size distribution, and ammonia concentrations were taken once per week, in addition to temperature and relative humidity measurements using a thermometer and sling psychrometer, respectively. Samples were taken between September 1999 and August 2000. Diurnal variations in airborne dust revealed an inverse relationship with changes in indoor temperature and, by association, changes in airflow rate. Ammonia levels changed despite relatively stable internal temperatures. This change may be related to both changes in flow rates and in volatility rates. As expected, contaminant concentrations increased during the cold weather months, but these differences were not significantly different from other seasons. However, total dust concentrations were very low (geometric mean = 0.8 mg/m^3) throughout the year. Likewise, ammonia concentrations averaged only 3.6 ppm in the well–maintained study site.

Keywords. *Animal housing, Air quality, Real–time sensors.*

A large increase in the number of intensive hog production facilities has been evident in recent years. Many studies have identified these "confinement" buildings as hazardous work places (Donham et al., 1989; Donham, 1990; Heederik et al., 1991; Barber et al., 1991; Larsson et al., 1994). These facilities are operated with a high animal density in buildings that are generally enclosed during the winter months to minimize heating costs. The combination of increased stocking density and low ventilation rates has contributed to poor indoor air quality (IAQ) within confinement buildings, which can be hazardous to workers' health (Takai et al., 1997).

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Although the gaseous portion of these airborne pollutants may be hazardous to health, particularly high ammonia concentrations (Donham et al., 1988), equal concern has been given to the high particulate portion. Microscopic analysis of dust in pig farms showed that feed and feces were the major constituents of dust in confinement buildings (Donham et al., 1986). Because of its organic origin, much of the airborne dust in a swine building can be considered a "bioaerosol," which includes bacteria, fungi, and their metabolic products. For example, endotoxin, a product of Gram–negative bacteria, has been shown to be an important indicator of the respiratory health status among swine building workers (Pickrell et al., 1993). The concentration of airborne dust in swine buildings may be affected by increased animal activities, low ventilation rates, feeding practices, bedding materials, flooring type, and dung and slurry handling (Preller et al., 1995; Takai et al., 1995). A study conducted to determine the amount of inhalable dust typically found in swine buildings in the Netherlands reported values ranging from 0.3 to 26.6 mg/m^3 (Preller et al., 1995), and a similar study performed in Iowa reported averages of 6.25 and 0.53 mg/m^3 for total and respirable dust by gravimetric determination, respectively (Donham et al., 1986).

Many swine buildings are built with manure storage structures below the slatted floors of the animal pens. Manure is typically stored for 3 to 9 months in a liquid form (10% solids) prior to removal for land application (Donham et al., 1988). In these pits, the manure undergoes anaerobic digestion, during which up to 40 different gases and vapors can be generated. Of these, methane (CH_4), hydrogen sulfide (H_2S), ammonia (NH_3), and carbon dioxide (CO_2) are the major compounds. Health problems associated with exposure to hydrogen sulfide and ammonia in swine buildings include irritation of the eyes, mucous membranes, and respiratory tract (Donham and Gustafson, 1982). The production of gases by manure stored in a swine building varies in relation to the age of the manure after pit cleaning, time of year, and animal age (Donham et al., 1988). Ammonia measurements in swine buildings varied between 13 and 76 ppm in one study. However, only a portion of the ammonia originated from manure in the pits; the rest originated from urine and manure that accumulated on top of the slatted floor (Donham et al., 1988).

Total dust and ammonia levels in the range of their respective threshold limit values (TLVs; ACGIH, 2000) have been shown to contribute significantly to respiratory disease in swine building workers (Donham et al., 1989; Robertson, 1993). However, a study by Donham et al. (1989) suggests that concentration levels less than 0.23 mg/m^3 for respirable dust, 2.4 mg/m^3 for total dust, and 7 ppm of ammonia, as measured by area samplers, should be maintained in a swine building to avoid significant decrements in workers' pulmonary function. Improving poor air quality in a swine building has resulted in improved human respiratory responses (Zhang et al., 1997).

The research presented here was undertaken as part of a larger research agenda that includes an analysis of the effect of ventilation rates on swine confinement building IAQ. This study had, as its primary goal, the development of an understanding of the temporal variation in airborne dust and gaseous ammonia concentrations within a working swine building. A secondary goal was to evaluate the accuracy of real–time sensors in the harsh environment of a swine building over a year–long period by comparison with active sampling methods. A complimentary study focused on the development of a computer simulation of a swine building ventilation system as it impacted IAQ and the environmental parameters temperature and relative humidity (Zhang et al., 2001). Therefore, a completely mechanically ventilated farrowing facility was chosen as the study site.

Methods

Study Site

Two air contaminants, ammonia and particulate matter, were monitored between September 1999 and August 2000 in a farrowing facility associated with the Swine Education Center of Kirkwood Community College of Cedar Rapids, Iowa. One room of the facility was used as part of this research. The room measured 7 m × 9 m and contained two rows of five pens each with a central aisle separating the rows. Floor grating separated the room air volume from the volume of air in the waste pit area. Air entered the room through adjustable vents located along the upper corner of each sidewall. One variable–speed fan (pit fan) pulled air through the room and down into the pit area before exhausting. Two fans (wall fans 1 and 2) were also mounted on the center of the outside sidewall to increase the air exchange rate as needed to decrease room temperature during warm days. A temperature controller (Varifan model ECS 5M, Multifan, Inc., Bloomington, Ill.) operated the fans, a space heater, and a water–misting system according to the following schedule relative to the setpoint temperature:

- +2.5°F (+1.4°C): wall fan 1 (variable speed) activated at 60% of maximum and ramped to maximum at +5°F.
- +5°F (+2.8°C): wall fan 2 (on/off) activated, and deactivated at +3°F.
- +10°F (+5.6°C): water–misting system activated.
- –2°F (–1.1°C): space heater activated, and deactivated at setpoint.

The 2°F difference between activation and deactivation of wall fan 2 and the space heater represents a "dead band" designed to minimize rapid on/off cycling when the temperature is near the activation temperature for each device. Furthermore, the pit fan was typically run continuously at 70% of maximum when the temperature was below the setpoint and ramped to its maximum speed when the temperature was 2.5°F above the setpoint. The controller did not contain monitoring capabilities, and it was not possible to continuously record the activity of the three fans over time. Therefore, this control strategy, together with the fan curves supplied by manufacturer, was used to estimate fan activity and, hence, the total airflow rate relative to internal temperature. The total flow rate varied between 0.6 and 5 m^3/s, equivalent to 10 and 85 air exchanges per hour, respectively.

Real–Time Sensors

One goal of this study was to determine the accuracy of the direct–reading instruments over time when compared to active sampling methods. Only the aerosol photometer was designed to enable a field check to re–establish a "zero" and "range" on a regular basis. Some of the sensors contained a trimming potentiometer to adjust their output relative to an active measurement. This was not performed, however, so that an indication of accuracy over time could be obtained and to establish the correlation between sensor readings and actively sampled data.

A current–transmitting meter was purchased to monitor outdoor temperature and relative humidity (HMW21YB, Vaisala, Helsinki, Finland). Likewise, a current–transmitting meter measured indoor relative humidity (HMW60U, Vaisala, Helsinki, Finland). Indoor temperature was recorded with an internal sensor associated with the datalogger used to record readings from all sensors (Smart Reader Plus 7, ACR Systems, Inc., Surrey, British Columbia). These instruments were initially operated in a laboratory and their readings verified relative to those taken by a certified thermometer and sling psychrometer.

Ammonia was measured using a direct–reading instrument (Ammonia–Stat, Industrial Scientific Corporation, Oakdale, Pa.). Prior to its application in the field, the ammonia sensor was calibrated with zero–air and a mixture of zero–air and 100–ppm ammonia span gas injected into a glass chamber to create a 25–ppm atmosphere. However, this instrument was not designed to allow field calibration and was not serviced during the study period.

Airborne dust concentrations were measured using an aerosol photometer (Handheld Aerosol Monitor, PPM, Inc., Knoxville, Tenn.). Instruments of this type do not distinguish between total and respirable dust, and their sensitivity varies with particle size (MIE, 1990). Therefore, the term "sensor–based dust concentration" is used here to indicate the general dust concentration measured by this instrument. This photometer can be set to read dust concentrations in a range of 0–2, 0–20, or 0–200 mg/m^3. The range was initially set at the 0–20 mg/m^3 range, but after 6 months of sampling the decision was made to change this to the 0–2 mg/m^3 range as dust levels were consistently low. This instrument was zeroed when exposed to filtered air. Likewise, a calibration device was provided to allow the user to reset the range of the instrument response relative to that suggested by the manufacturer after inserting the element. On a weekly basis, the photometer was cleaned by spraying the "view volume" of the sensor with filtered air, re–zeroed, and the response checked with the calibration element. The photometer had also been previously calibrated during a separate study by injecting ISO fine test dust (Powder Technology Inc., Burnsville, Minn.) into a well–mixed chamber to demonstrate a linear response with changes in both total and respirable dust concentrations (O'Shaughnessy and Slagley, 2002). However, when measuring any other type of dust than that used for calibration, these instruments will provide a reading proportional to the actual concentration and not necessarily equivalent to the actual concentration because of differences in the density of the measured dust relative to that of the calibration dust.

The sensors and datalogger were mounted on a 40 cm × 50 cm plywood board and suspended in the center of the study room and 180 cm above the floor so that workers could pass under them easily while performing chores. The sensors were all operated in a "passive" mode rather than incorporating a pump to actively pull air through the sensors. The study room of the farrowing facility was occupied by pigs on an approximately 3–week basis, followed by 5 to 7 days for cleaning before the facility was used again. Therefore, the readings were only taken during animal occupancy.

The datalogger used during this study was only capable of retrieving and storing a voltage signal from a sensor in the range of 0 to 5 V. The aerosol photometer produced an output voltage of 0 to 2 V proportional to 0 to 20 mg/m^3. Therefore, a voltage amplifier was used to increase the output by a factor of 2.5 to take advantage of the full range of the datalogger. Furthermore, both the relative humidity sensor and the ammonia sensor produced a current signal of 4 to 20 mA proportional to the full range of each instrument (0% to 100% and 0 to 100 ppm, respectively). Therefore, 250 Ω resistors were used to produce a voltage ranging from 1 to 5 V from the 4 to 20 mA signal transmitted by the sensors. The voltage readings were recorded by the datalogger every 4 minutes and downloaded to a personal computer once during each week of sampling. These readings were then imported into a spreadsheet for conversion to the physical values represented by each voltage reading.

An analysis to indicate whether sensor response changed over the course of the sample period was performed by comparing the ratios of the time–weighted average (TWA) of sensor measurements to the measurement by the corresponding active sampling method during the coincidental sample period. Quality control charts were developed to plot the sequence of ratios determined for each sampling period (Montgomery, 1991). These plots included horizontal lines indicating the overall average as well as the lower and upper confidence limits defined as three standard deviations from the mean. The charts were then used to determine whether a significant drift in instrument response had occurred by noting whether a sequence of ratios was plotted outside the confidence limits.

Active Sampling

Once per week while animals were present, 8–hour active samples were taken for particulate matter and ammonia. A measure of total dust was taken as per NIOSH Method 0500 with the exception of using an "open–face," rather than "closed–face," filter cassette (NIOSH, 1994). A cyclone dust sampler (BGI, Inc., Waltham, Mass.) was used to measure the respirable fraction of the total dust, and a 4–stage cascade impactor (Series 290, Anderson, Inc., Smyrna, Ga.) was used to determine the particle size distribution. Results from this device were expressed in terms of the geometric mean and geometric standard deviation of the aerosol size distribution under the assumption that the aerosol had a lognormal distribution (Cooper, 1993). Sampling was carried out using a large pump attached to a long piece of vinyl tubing draped over the sampling board. The tube was branched out using Y–connectors, which in turn were connected to flow restrictors (critical orifices) that produced a desired flow rate of 2.0 L/min for total dust and cascade impactor sampling, and 4.0 L/min for respirable dust sampling. The necessary flow rate for all samplers was provided by a single rotary–vane vacuum pump.

Filter weighing was conducted in a climate–controlled room with a six–place balance. Three field blanks for both the dust samplers and the impactor were analyzed with each set of weekly samples. Sampler flow rates were calibrated weekly with an electronic soap–bubble flow meter by taking the average of 6 successive measurements. The room controller settings were also noted weekly, as was fan operation.

Active sampling of ammonia was conducted using sulfuric–acid–treated silica gel sorbent tubes (SKC, Inc., Eighty Four, Pa.) as per NIOSH Method 6016. A critical orifice providing a flow rate of 0.30 L/min was used to draw air through the sorbent tube and was calibrated on a weekly basis. After storage in a refrigerator, the silica gel was removed from each tube, desorbed in distilled water, and 50 μL of the desorbed solution was injected into an ion chromatograph for analysis relative to prepared standards. Blanks were analyzed along with standards.

Relative humidity and temperature measurements were taken using a certified sling psychrometer and associated dry–bulb thermometer, respectively. These measurements were compared to measurements taken from the datalogger at the same time as those taken with the psychrometer. This comparison was made at both the beginning and end of each sample period. The reported accuracy and/or limit of detection (LOD) of both the sensors and active sampling methods are given in table 1.

Statistical Analysis

A comparison between the concentration measured with the active sampling methods for total and respirable dust and ammonia and the time–weighted average of voltage readings provided by the respective sensors over the corresponding sampling interval was made by computing the Pearson correlation coefficient (R) for each data set. This analysis was performed for samples collected within each of four seasons: fall (September, October, November), winter (December, January, February), spring (March, April, May), and summer (June, July, August). Likewise, R was computed for the sets of data corresponding to single measurements taken by a thermometer and sling psychrometer and the corresponding real–time voltage signals provided by the respective sensors except for the case of internal temperature, in which the sensor–based measurements were given in units of °C directly. A one–way analysis of variance was used to determine whether there was a statistical difference at the 95% confidence level between active sampling methods taken each season.

Table 1. Sensor and sampling method accuracy and limit of detection (LOD).

	Accuracy	LOD
Sensors		
Aerosol photometer	—	0.005 mg/m^3
Ammonia	±5% of reading	—
Internal temperature	—	0.07°C
Internal humidity	±2% RH	—
External temperature	—	0.07°C
External humidity	±2% RH	—
Sampling Methods		
Total dust	±11%	0.03 mg/m^3 [a]
Respirable dust	—[b]	0.03 mg/m^3 [a]
Ammonia	±14.5%	—
Thermometer	—	0.25°F
Sling psychrometer	±5% RH	—

[a] At flow rate and sample time used in this study.
[b] Depends on aerosol size distribution.

Results

A total of 34 weeks during the period between September 1999 and August 2000 were sampled. However, some technical difficulties (see Discussion) prevented the use of information gathered in some weeks for a particular instrument. Therefore, in addition to the ability to obtain two measurements of temperature and humidity per week and only one for each dust type and ammonia, the sample size for comparison purposes differs by instrument.

Because the relative accuracy of each sensor was a primary consideration associated with this study, a determination of this accuracy was performed initially. This work was followed by an analysis of the time–varying nature of the readings over the weeks during which recordings were made. Therefore, results are presented in a similar order that first indicates the accuracy of each instrument and then demonstrates the daily and seasonal variations in readings recorded in the swine building room.

Sensor Accuracy

The Pearson correlation coefficients (R) between the time–weighted average (TWA) of voltage signals provided by the various sensors used during this study and the associated TWA obtained by active sampling are listed in table 2 for each season and all samples. The p–values associated with a test of the significance of each R value are also listed in table 2. The correlations were strongest for the sensors used for temperature and relative humidity and weakest for the dust and ammonia sensor.

Correlations for ammonia and dust sensors also varied considerably between seasons. As shown in table 2, except for total dust, the correlations were highest and most significant for readings taken in the fall. This corresponds to the period when the instrumentation was first used and was therefore most accurate. Some correlations shifted from positive to negative between seasons, ammonia for example. This is more an indication of the overall lack of significance of some R–values rather than an indication of a significant change in sensor response. Furthermore, the low correlation in external humidity during the winter was a consequence of being unable to accurately detect relative humidity with the sling psychrometer when the temperature was below freezing.

Table 2. Indoor air quality factors in a swine building measured with standard and sensor–based methods.

		n	Min.	Max.	Mean[a]	Std. Dev.[a]	R[b]	p–value
Ammonia (ppm)	Fall	4	3.21	7.19	4.91	1.55	0.957	0.043
	Winter	5	1.26	10.31	3.64	2.57	0.900	0.100
	Spring	4	1.53	4.68	2.19	1.67	–0.774	0.226
	Summer	5	0.57	7.40	1.96	2.81	0.850	0.068
	Year	18	0.57	10.31	2.89	2.60	0.683	0.002
Total Dust (mg/m^3)	Fall	4	0.52	1.09	0.82	1.37	–0.199	0.801
	Winter	5	0.49	3.09	1.17	2.10	0.913	0.030
	Spring	4	0.22	1.31	0.69	2.17	0.919	0.081
	Summer	5	0.25	0.97	0.49	1.70	–0.737	0.155
	Year	18	0.22	3.09	0.75	1.94	0.338	0.170
Respirable Dust (mg/m^3)	Fall	4	0.10	0.32	0.17	0.10	0.757	0.243
	Winter	5	0.19	0.35	0.23	0.07	–0.243	0.694
	Spring	4	0.11	0.27	0.18	0.07	–0.518	0.482
	Summer	5	0.04	0.32	0.17	0.12	–0.742	0.151
	Year	18	0.04	0.35	0.19	0.09	–0.022	0.930
Internal Temperature (°C)	Fall	14	18.89	27.22	22.98	2.28	0.822	<0.001
	Winter	18	13.33	24.44	20.49	2.86	0.919	<0.001
	Spring	12	18.89	24.44	21.57	1.85	0.692	0.013
	Summer	18	23.33	33.89	26.02	2.72	0.936	<0.001
	Year	62	13.33	33.89	22.87	3.32	0.872	<0.001
External Temperature (°C)	Fall	14	9.44	23.89	15.52	4.87	–0.885	<0.001
	Winter	6	2.78	13.89	8.43	3.79	–0.255	0.626
	Spring	13	2.78	26.67	12.18	7.43	–0.323	0.281
	Summer	6	21.11	29.44	25.56	3.12	–0.914	0.011
	Year	39	2.78	29.44	14.86	7.48	–0.552	<0.001
Internal Humidity (%)	Fall	14	42	80	61.07	9.40	0.676	0.008
	Winter	18	58	94	69.67	7.77	0.751	<0.001
	Spring	13	50	86	62.62	10.01	0.954	<0.001
	Summer	19	50	88	72.95	12.92	0.475	0.040
	Year	64	42	94	67.33	11.21	0.684	<0.001
External Humidity (%)	Fall	14	42	100	71.07	14.45	–0.710	0.004
	Winter	6	74	100	92.67	10.33	0.143	0.787
	Spring	12	48	100	76.92	17.13	–0.796	0.002
	Summer	16	42	91	72.25	13.75	–0.768	0.001
	Year	48	42	100	75.63	15.67	–0.600	<0.001

[a] Values for total dust and ammonia are represented by geometric means and geometric standard deviations. All others are arithmetic means and standard deviations.
[b] Pearson correlation coefficient between standard and average of sensor output readings, with related p–value on test of H_o: R = 0.

An example of the quality control charts developed to determine sensor drift is given in figure 1. As shown in this figure, using data from the temperature sensor and thermometer, one ratio was significantly different from the other ratios. Regardless, no identifiable trend is evident, nor were a series of ratios plotted beyond the control limits, which would indicate a significant drift in instrument response. Similar plots made for the other sensors likewise did not reveal a significant trend over time. The quality control plot for the ammonia sensor revealed that the ratio of sensor to standard method remained relatively stable through the first 5 months of the study, with a mean and standard deviation of 1.79 and 0.31, respectively, but it was higher and more variable during the final 7 months of the study, with a mean and standard deviation of 3.8 and 2.34, respectively.

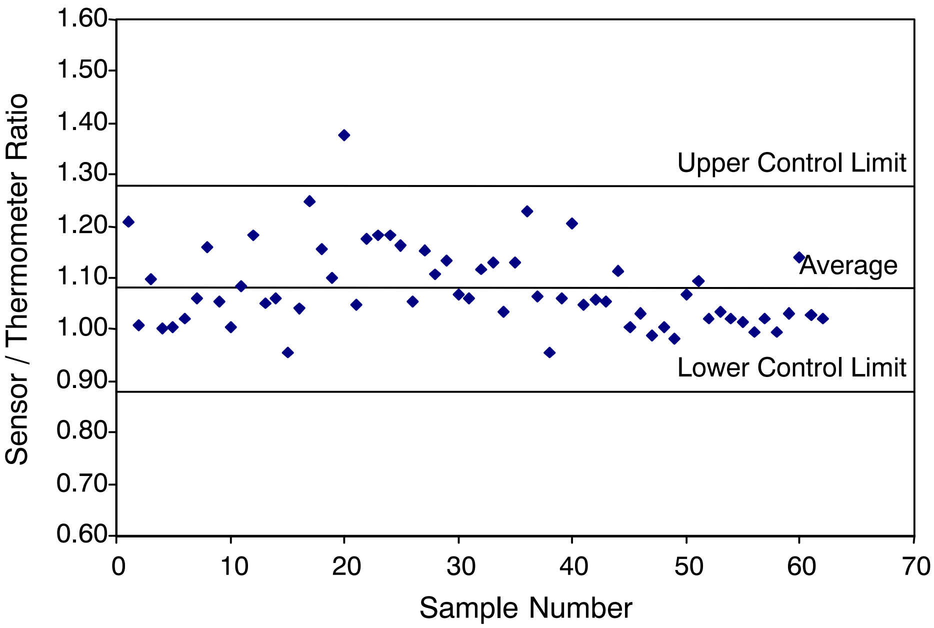

Figure 1. Quality control chart of the ratio of sensor to thermometer readings for indoor temperature showing overall average line and control limits.

Daily Variations

In general, daily variations in both indoor environmental and contaminant measurements varied more during warm weather than cold weather. For example, as shown in figure 2, diurnal variations in sensor–based dust concentration were evident over several days in May when external temperatures varied from 17°C to 31°C. As shown in figure 2, the temperature control system kept the room temperature from dropping below a setpoint temperature of 23°C (72°F) by both minimizing fan use and operating a space heater as needed. However, as external temperatures increased during the day, the internal temperatures rose to 28°C (82°F) despite the activation of the wall fans according to the schedule given above. Therefore, a flat internal–

temperature profile was not obtainable under these conditions. A display of the total airflow rate through the room relative to internal temperature is given in figure 3. The flow rate represents an approximation based on the controller scenario given above and demonstrates how the maximum flow rate was obtained when the internal temperature was greater than the wall fan 2 setpoint and continued to rise. This increase in flow rate corresponds to the decrease in sensor–based dust concentrations displayed in figure 2 (fig. 4).

Conditions monitored during cold periods, when only the pit fan was operating at a low speed, typically showed relatively stable airborne dust readings over time (fig. 5). During these times when the external temperature was continuously below the setpoint, there was little difference between night and day concentrations, as only the pit fan was operated at it minimum speed. The rapid change in indoor temperature shown in figure 5 during short time periods early in the sample period was noticed in other plots. These changes were associated with times when the external temperature was low and the space heater was turned on and off in a cyclic manner as the indoor temperature periodically dropped below the setpoint for activation of the heater. Daily oscillations in ammonia concentrations were also evident; however, these oscillations often occurred during weeks when the indoor temperatures, and hence airflow rates, were relatively stable (fig. 6). This was typical of most plots made of ammonia throughout the sample year. Ammonia concentrations may be sensitive to slight changes in airflow rate and/or slight variations in indoor temperature that affect generation rates from the pit and from surfaces coated with urine that could not be measured with the instruments utilized during this study.

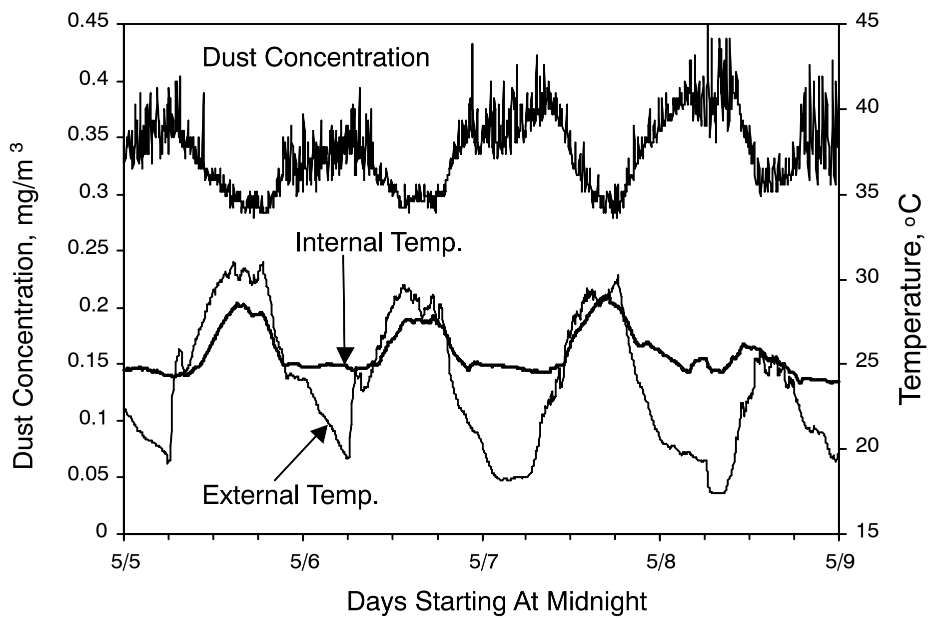

Figure 2. Sensor–based dust concentrations relative to internal and external temperatures during a warm weather period (May).

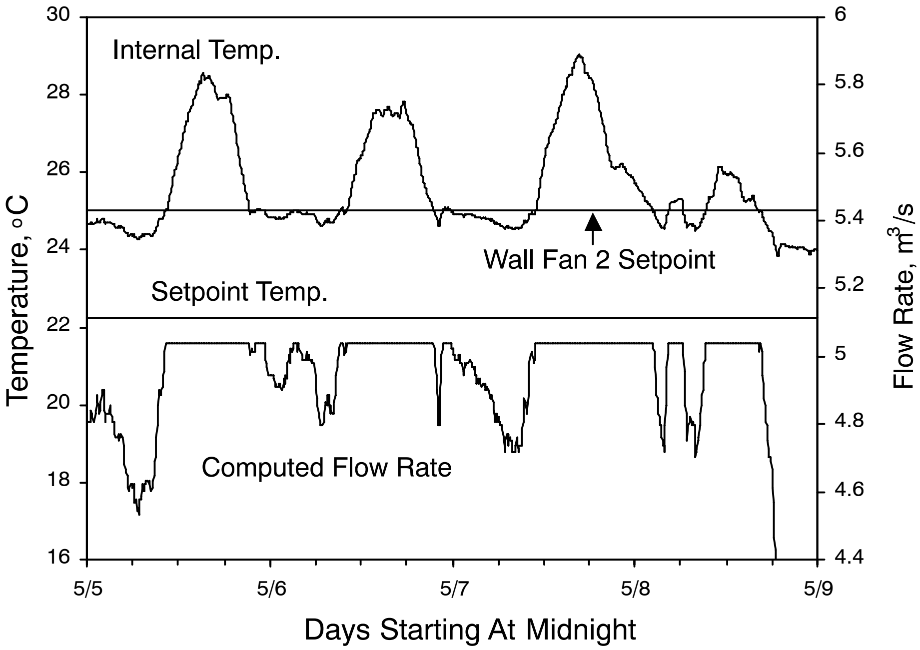

Figure 3. Computed airflow rate from controller algorithm and settings in relation to internal temperature.

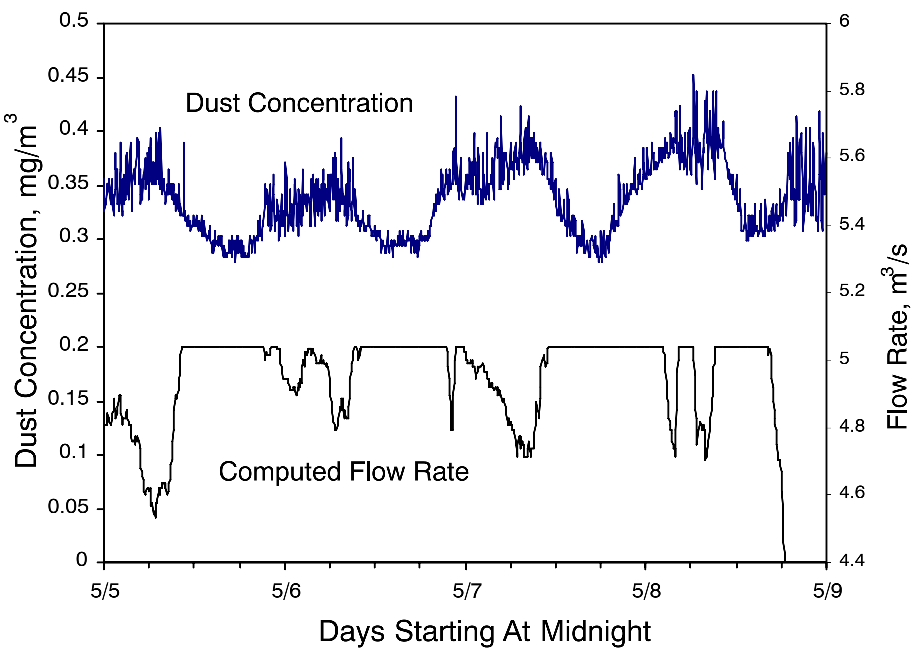

Figure 4. Sensor–based dust concentrations relative to the computed airflow rate from controller algorithm given in figure 3.

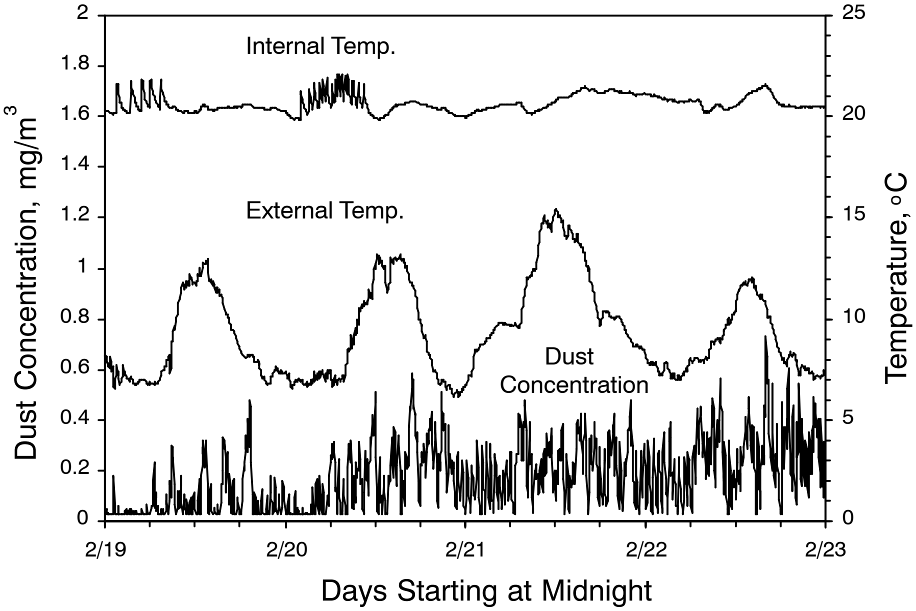

Figure 5. Sensor–based dust concentrations relative to internal and external temperatures during a cold weather period (February).

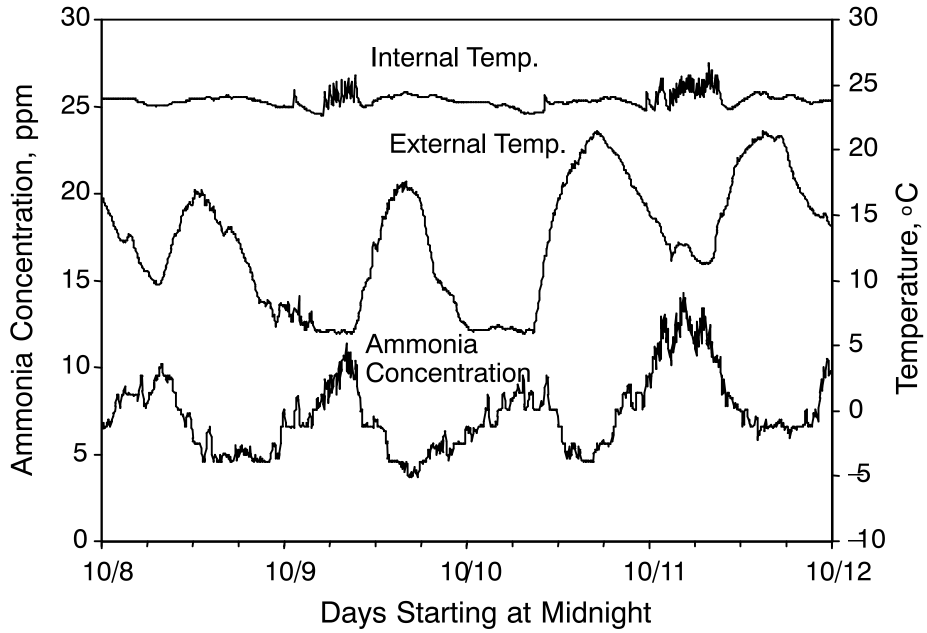

Figure 6. Ammonia concentrations relative to internal and external temperatures during a cold weather period (February).

The previous figures showed airborne dust and ammonia concentrations with no significant trend over the week plotted. However, many plots made of weekly samples showed an upward trend in both measurements, apparently due to a real increase in these concentrations with time of use by the animals. As shown in figure 7, a typical 3–week series of measurements demonstrates an ever–increasing trend in both ammonia and sensor–based dust concentrations. This pattern would then repeat during the next 3–week period after removal of the sows and piglets and subsequent power–wash of the room. Because the ammonia sensor was not serviced during the 3–week period shown in figure 7, the concentration levels are contiguous from week to week. However, the photometer readings show a sudden drop at the beginning of each sample week after servicing by spraying any accumulated dust from the dust–sensing region. This indicates that an unknown fraction of the increase in airborne dust measured over a week was due to buildup of dust in the instrument.

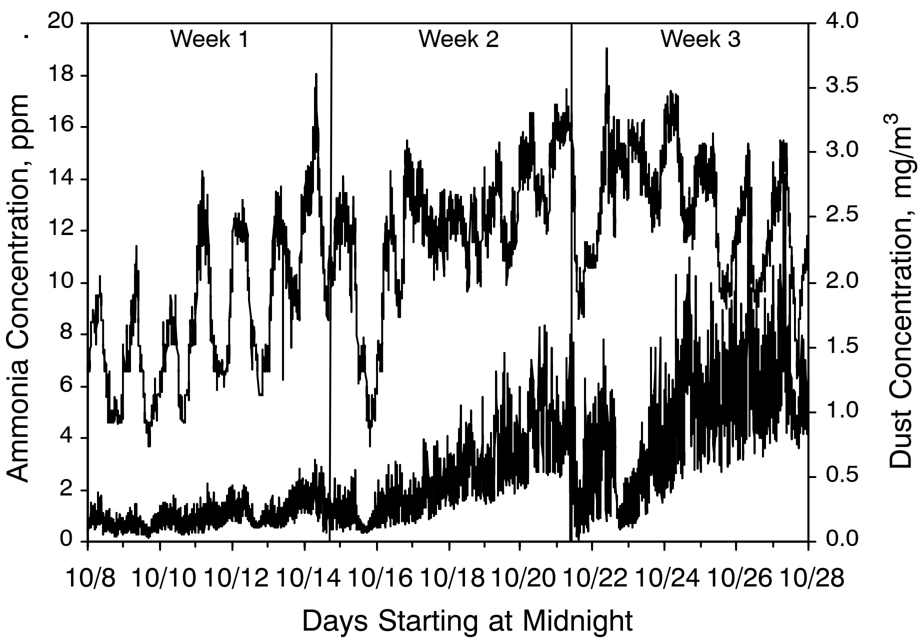

Figure 7. Changes in ammonia and sensor–based dust concentrations over a three–week period.

Seasonal Variation

The sample size, mean, standard deviation, and range of active sample results taken during each season and over the entire year are given in table 2. A normality test (W–test) was performed on each set of samples taken over the year. Of the various parameters measured in this study, total dust and ammonia concentrations were best described by a lognormal distribution. Therefore, all means and standard deviations in table 2 are arithmetic except for those associated with total dust and ammonia, which are expressed as geometric means and geometric standard deviations.

As shown in table 2, the dust levels in the swine building were very low relative to the threshold limit values (TLVs) of 10 mg/m^3 and 3 mg/m^3 for total and respirable dust, respectively (ACGIH, 2000). The maximum level of 2.4 mg/m^3 for total dust recommended by Donham et al. (1989) was exceeded in 2 of the 21 weeks for which data were obtained. Likewise, the recommended maximum level of 0.23 mg/m^3 for respirable dust was exceeded in 6 of the 21 weeks for which data were obtained. The measured levels changed with the seasons, but a single–factor analysis of variance performed on total and respirable dust concentrations revealed no significant difference across seasons at the 95% confidence level ($p = 0.21$ and $p = 0.68$, respectively). This lack of significance may be partly due to a relatively low sample size. As expected, however, total dust concentrations during the winter months (December, January, February) were over twice those measured in the summer months (June, July, August). The particle size distribution, as measured by the cascade impactor, remained relatively constant throughout the year, with median diameters ranging between 11 μm (winter) and 14 μm (fall). The average percent of respirable dust to total dust over all samples was 25%.

Ammonia concentrations across seasons were not significantly different ($p = 0.33$) and were greatest in the fall (September, October, December) with values approximately twice that of spring (March, April, May) and summer. The maximum level of 7 ppm for ammonia recommended by Donham et al. (1989) was exceeded during 4 of the 17 weeks for which ammonia samples were analyzed.

Discussion

As mentioned above and shown in table 1, the sample sizes associated with the evaluation of the individual sensors used during this study differed. Loss of information resulted from either a failure to obtain data from a sensor recorded over a particular week and/or problems in conducting the active sampling method. There were numerous weeks (13) when aerosol photometer recordings were not obtained. Initially, this resulted from a faulty electrical ground associated with the photometer power supply. There were also occasions when inaccurate readings occurred during the week after remounting the board after the room was power–washed.

The number of reliable ammonia comparisons was reduced when a large set of ammonia samples (17) was not analyzed correctly by the laboratory doing the analysis. This method required the use of an ion chromatograph to determine the amount of ammonia captured on the silica gel. We found that the type of distilled water and the type of column used in the chromatograph affected the results obtained. In addition, the stated accuracy of the method is ±14.5%. Therefore, some of the variation between sensor and active sampling method can be attributed to variability in the active method. Furthermore, the type of ammonia sensor used is still being evaluated by the manufacturer and is known to be sensitive to changes in relative humidity.

In addition to a small sample size, the lack of association between the dust monitor and active samples found in this study can be caused by a true difference in dust concentration over even a small distance in poorly mixed areas. The dust levels were also very low due to the frequent cleaning of the room, a condition that can exacerbate spatial differences. A number of studies have indicated that aerosol photometers are often inaccurate, despite their wide use, especially when sensing an air volume that contains a mixture of dust types (O'Brien et al., 1989) or when the particle size distribution of the aerosol changes over time (Willeke and Baron, 1990).

O'Shaughnessy and Slagley (2002) found a highly correlated linear relationship between changes in concentrations of both organic and inorganic dust when the photometer used in this study was calibrated in a well–mixed chamber. However, the relationship between monitor response and gravimetric measurements changed significantly if the size distribution of the dust was intentionally changed. It was also evident from the photometer readings that the sensor's optics were increasingly dirtied during a week–long sample period with a corresponding increase in measured concentrations. A final consideration involves the nature of the comparison method. O'Shaughnessy and Slagley (2002) employed active sampling through the photometer by attaching a filter directly to the view–volume of the photometer. All dust collected on the filter therefore passed through the photometer. In the present study, dust particles moved through the photometer by eddy currents and/or diffusion, and the resulting concentration was compared to a filter sample taken several centimeters away. The photometer was operated passively in this study to simulate the method most likely to be used in swine buildings. Although unsubstantiated, it is reasonable to assume that this comparison method will not result in as high a correlation as that obtained by active sampling.

In order to establish the reliability of real–time sensors while operating in a swine building, the particular sensors used were not adjusted during the study period. The control charts made for each sensor during this study did not reveal the need to adjust a sensor and/or replace parts. The variation in correlation values between seasons for some sensors, however, suggests the possibility of variations in sensor response over shorter time periods than one year. Changes in sensor response should be undertaken with caution. An adjustment to the sensor output signal should only be made if it has been determined that a significant trend away from an accurate reading has taken place (Jordan, 1997). A number of comparisons (say, $n > 20$) over a relatively long time period are needed to establish the existence of a significant change in sensor output. Frequent adjustments may only be responding to random differences between sensor and sampler. In that case, the sensor can be made less accurate by over–correcting the output signal (MacGregor, 1990).

Changing patterns in the diurnal variation of ammonia and sensor–based dust concentrations between seasons was observed. These changes suggest that, in general, contaminant concentrations remain relatively high and stable during the winter months when external temperatures are consistently below the room setpoint temperature and, therefore, airflow rate remains at its minimum level. Likewise, concentrations are lower but unstable in warmer months when external temperatures fluctuate relative to the temperature setpoint and fan activity changes between day and night. Recordings of days when contaminant concentrations changed over time suggest that these concentration levels are influenced by flow rate through the room. Therefore, some mitigation of contaminant levels is possible by the dilution effect of higher airflow rates. This observation suggests that a system to automatically adjust flow rate to decrease contaminant levels could be implemented in a swine building. However, such a system would necessarily have to rely on sensors designed to read accurately in the harsh environment of a swine building, and must consider the competing cost of operating fans at a higher speed as well as the additional cost associated with heating more air in cooler months.

Conclusions

Real–time sensors were used to continuously monitor both the environmental parameters (temperature and relative humidity) and two airborne contaminants (dust and ammonia) to determine the daily and seasonal variation in these parameters as indicators of the overall quality of air in a working swine confinement building. The measurements made with these instruments were compared to established sampling methods. A relatively good association was obtained between the sensors used to obtain the environmental measurements (temperature and humidity) and their corresponding sampled data. However, the time–weighted average of readings from the sensors for ammonia and airborne dust did not correlate well with measurements derived from active sampling methods and were, therefore, unreliable for indicating accurate concentration levels on a real–time basis. Given their lack of accuracy, readings from these instruments were only useful for determining the relative changes in contaminant levels as affected by changes in internal temperature, and by association air flow rate, through the swine building. An aerosol photometer containing an internal pump to continuously clean the optical sensor is recommended for use under these conditions. Likewise, an ammonia sensor designed to be easily serviceable and calibrated is needed. A causal link was established during this study between airflow rates and dust concentrations but not ammonia concentrations. This link suggests that changes in airflow rates may be used to mitigate dust concentration levels, but further work is needed to determine the cost–to–benefit relationship of this form of contaminant control.

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