AMMONIA DISTRIBUTION IN A PIT-VENTILATED CONFINEMENT BUILDING: ONE-HALF SCALE MODEL STUDY

J. J. Buiter, S. J. Hoff

ABSTRACT. *A one-half scale model of a pit-ventilated swine confinement barn was used to study the effects of building design and management factors on the distribution of ammonia in the airspace. Two slat orientations, two manure depths (full and empty), and two ventilation rates, representative of winter conditions, were compared. As expected, the ventilation rate was a major factor in determining average levels of ammonia in the airspace. Manure depth significantly affected ammonia levels and gas distribution in the airspace above and below the slatted floor. Large stagnant regions were observed in the manure pit head-space for a nearly empty manure pit. Floor slat orientation did not appear to significantly affect average ammonia levels or the distribution of ammonia in the airspace, although some effects may have been present at the higher ventilation rate tested.*
Keywords. *Air contaminants, Air quality, Pit ventilation, Slatted floors, Swine housing.*

Confined buildings for swine are popular in the pork industry today due to their efficiency, including savings in labor and space. Proper design and management enable the producer to maintain accurate control over the environment in these buildings. Due to the nature of confined spaces, it is critical that adequate ventilation is maintained to remove excess heat, moisture, and contaminants produced by animals in the building. Failure to maintain proper environmental conditions will increase health problems, hasten deterioration of structural components, and reduce productivity.

The purpose of the ventilation system is to maintain a thermal design condition while controlling levels of humidity and gaseous contaminants introduced by the animals and their waste. Adequate heat and humidity production data are available for the design of acceptable psychrometric conditions for swine; however, there is very little information describing the production rates and dispersion of manure gases in swine confinement buildings. In addition, the complexity of air motion in these buildings makes it difficult to predict the effects of a particular ventilation system on contaminant removal.

The Occupational Safety and Health Administration (OSHA) governs employee safety issues for U.S. industry, including air quality concerns. OSHA regulations do not currently apply to livestock housing systems. The gaseous contaminants of primary concern in swine confinements are carbon dioxide, ammonia, hydrogen sulfide, and methane. Of these, ammonia is a significant contributor to health problems and equipment deterioration. Ammonia levels in excess of the OSHA limits for non-agricultural sectors are commonly found in many modern swine facilities.

Ventilation design characteristics that may affect ammonia levels in a building include: the location of air inlets and outlets, the total ventilation rate, obstructions to airflow, and temperature profiles within the space. Finally, the waste management system must not be overlooked in the analysis of air quality; manure gas production rates are heavily influenced by the local environment.

The primary objectives of this research were to quantify the distribution of ammonia in a pit-ventilated confinement building and to identify building design and management factors that significantly affect the performance of pit ventilation in terms of air quality. The specific objectives of this research were to: (1) physically reproduce ammonia production in a representative confinement building using a scale model; and (2) determine the effects of ventilation rate, slat orientation and manure depth on the distribution of ammonia in the human and animal occupied zones.

LITERATURE REVIEW

Ammonia in its gaseous form is an irritant, especially affecting mucous membranes (*CGA Handbook of Compressed Gases*, 1990). Although it is not toxic at levels found in animal confinement buildings, it may cause decreased production rates and chronic health problems in most animals and human workers (Stombaugh et al., 1969; Drummond et al., 1980; Donham et al. 1977; Donham, 1982).

The American Conference of Governmental Industrial Hygienists (ACGIH) recommends acceptable human workplace limits for contaminants. Limits for ammonia are currently set at a 25 ppm TWA (8-h time-weighted

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average) and a 35 ppm STEL (15-min short-term exposure level) (ACGIH, 1984). The National Institute of Occupational Safety and Health (NIOSH) recommends a 5 min ceiling limit of 50 ppm (OSHA, 1992). OSHA has proposed legislation that includes Permissible Exposure Levels (PELs) for agricultural operations with greater than 10 employees. Citing a high rate of illness and of toxic gases produced in manure pits, the proposed PEL for ammonia would be a 35 ppm STEL, based on the ACGIH guidelines and concern over potential long-term chronic effects (OSHA, 1992).

In swine confinement buildings, ammonia is produced by aerobic and anaerobic bacterial activity in manure, converting uric acid to ammonia and ammonium ions (Liao, 1989; Zhang et al., 1991). Ammonia is readily absorbed by water; Muehling (1970) found that gas levels were higher in confinements with solid floors than in those with under-floor pit storage, concluding that water in the manure pits was absorbing some of the ammonia. Models by Anderson et al. (1987) and Zhang et al. (1994) indicate that ammonia released from manure pits is increased by increasing ambient temperature and air velocities over the manure surface. Fisher and DeShazer (1972) showed that ammonia levels increased when manure surface area and local air velocities were increased.

Swine confinements frequently experience levels of ammonia in excess of recommended limits. Studies by Donham et al. (1977) and Donham (1982) found that wintertime ammonia concentrations ranged from 20 to 200 ppm; the majority of buildings tested met or exceeded the ACGIH 25 ppm TWA limit. In a wintertime test of air quality in farrowing barns, Clark and McQuitty (1988) measured daily averages of 10 to 50 ppm, even though the ventilation rate was higher than recommended for wintertime conditions. Sutton et al. (1987) measured ammonia concentrations as high as 30 ppm in a swine confinement with pit ventilation; levels in the confined building were higher than ammonia levels in an open-front building. Meyer (1987) reported wintertime ammonia levels of 36 to 54 ppm in total slat floor buildings with under-floor manure storage, noting that ammonia is one of the most common environmental problems in confinement facilities.

There may be a considerable amount of spatial variability of ammonia concentrations in a confined space. Brannigan and McQuitty (1971) and Skarp (1975) found exponentially decreasing levels of ammonia as the distance above the source increased for both solid and slatted flooring. De Praetere and Van Der Biest (1990) measured a significant variation in ammonia levels throughout the width of a building cross-section as a result of airflow patterns extending into the manure pit area.

Ventilation

Ventilation rate has a significant effect on the levels of ammonia in a swine confinement building. Brannigan and McQuitty (1971) showed that ammonia levels decreased with an increasing ventilation rate in a chamber with simulated production rates. A study by West (1977) of air quality in industrial applications indicated that the ventilation rate affected the amount of mixing that occurred in a space; when a gas source was located in a stagnant zone (as may be the case in an under-floor manure pit), decreasing the ventilation rate increased the average gas concentration in the room.

Gustafsson (1987) showed that ammonia levels decreased at locations 0.3 m (12 in.) and 1.5 m (59 in.) above the slatted floor in a pig confinement when ventilation was increased; however, increasing the ventilation rate above a minimum level had little effect on ammonia concentrations. A computer model by Hoff and Bundy (1992) showed a similar relationship between ammonia levels and the ventilation rate.

The air inlet system also affects the distribution and levels of ammonia in a confinement building. Skarp (1975) and Gustafsson (1987) showed that inlet design and location determined the distribution of gaseous contaminants in a confinement building. Gustafsson (1987) found that for wall exhaust systems with ceiling inlets, increasing the ventilation rate actually increased the release of ammonia into the occupied zones, likely due to increased air movement near the manure surface.

Schulte et al. (1972) suggests that ammonia may be forced up from under a slatted floor by prevailing airflow patterns, based on a study of buildings with total and partially slatted flooring. De Praetere and Van Der Biest (1990) found a significant amount of spatial variability in a hog confinement due to airflow patterns extending into the manure pit area of a total-slat flooring system. The result was that ammonia was being introduced into the occupied zones at one end of the building. Yu et al. (1991) showed that inlet conditions affected the air exchange rate between the manure pit airspace and the occupied zone; increasing velocities over the floor increased the exchange rate between the two zones. Jin and Ogilvie (1992) showed that floor velocities were related to inlet velocities and momentum for a number of inlet systems, indicating a connection between inlet design and contaminant distribution in confinement buildings.

Localized Exhaust

Industrial ventilation practices suggest placement of the air exhaust near the source of the contaminant; the operator (or objects of concern) should be located between the air inlet and the contaminant source (ACGIH, 1992; ASHRAE, 1997). One method of controlling gaseous contaminants in an under-floor manure pit is to place an exhaust fan below the floor, a technique known as pit ventilation. Two types are generally used: a fan outlet or annex may be placed directly in the wall below the floor, or a perforated duct can be installed below the floor with a fan on one or both ends (MWPS, 1987; Driggers, 1975). The duct method is more expensive, but provides better exhaust distribution; ducts are typically constructed from plastic pipe or plywood (MWPS, 1987).

One limitation of localized exhaust is the small zone of influence of air outlets; for a circular opening, the air velocity is less then 10% of the face velocity within one diameter of the exhaust location. In contrast, an inlet jet of the same dimensions can maintain 10% of the face velocity as far as 30 diameters from the inlet (ACGIH, 1992). Therefore, the placement and design of the inlet system is a critical component of the ventilation system (ACGIH, 1992; ASAE EP470, 1993b).

Keller and Day (1975) found that pit ventilation reduced odors in confinement buildings, noting that a properly designed system had a measurable downdraft at the slatted floor surface. Ross et al. (1975) tested a tapered pit duct design and reported that pit ventilation reduced average ammonia levels in the occupied zone of the building. They concluded that it was easier to design a system for pit ventilation only when compared to a system with a combination of above-floor exhaust and pit ventilation. Ross et al. (1975) also suggested that there is a minimum ventilation rate required to prevent pit gases from entering the occupied zone. Gustafsson (1987) compared buildings with above-floor exhaust to buildings with pit exhaust; pit ventilation reduced ammonia levels by 25 to 30% in the occupied zones. Breum et al. (1990) found that a pit ventilation system had better ventilation efficiency at high airflow rates, but that the above-floor exhaust system outperformed the pit exhaust system at low ventilation rates.

Grub et al. (1974) found that the perforated duct design provided a more uniform downdraft at the floor surface than the annex type of pit ventilation, noting that a minimum floor downdraft of 0.081 m/s (16 ft/min) was necessary to prevent the movement of air from the pit to the occupied zone. Buller and Hellickson (1978) conducted a study of several pit ventilation scenarios in a 1/12 scale model. They found that a centered duct pit ventilation system with partially slatted flooring exhibited the best overall ventilation performance. Pohl and Hellickson (1978) compared five types of pit ventilation systems in a 1/12 scale model and concluded that the centered duct system produced the best ventilation characteristics. The annex design resulted in nonuniform airflow patterns in the building, including upward air movement from the pit to the occupied zone. Pit ventilation was found to affect air velocities in the manure pit head-space; air inlets interacted with the pit ventilation design.

Flooring

Floor design can affect the distribution of contaminants in an enclosed building. Grub et al. (1975) found that the width of the slots in a slatted floor affected the downdraft performance of the annex type of pit ventilation. Buller and Hellickson (1978) found that the amount of slatted flooring in a pit-ventilated building affected air velocities at the animal level; however, there was no effect at the pit level. A recently introduced flooring design uses variable slot size and spacing to improve pig comfort and to reduce air exchange between the pit and the occupied zone (Duxbury-Berg, 1995).

Manure Management

The depth of the manure in the pit may affect the degree of interaction of the manure surface with the ambient environment. Schulte et al. (1972) found that the depth of manure in a pit affected air velocities above the slatted floor in a pit-ventilated scale model building. The magnitude of the effect depended on the inlet system. However, Buller and Hellickson (1978) did not observe any effect of manure depth on airflow patterns above or below the floor in a scale model pit-ventilated building.

Materials and Methods

A scale model section of a typical swine confinement building was used to examine the effects of ventilation rate, slat orientation, and manure depth on the distribution of gaseous ammonia in the airspace above the floor. The ventilation rates tested were representative of winter minimum requirements; all ventilation air was exhausted through the pit ventilation system. For this study, only isothermal conditions without obstructions were tested, i.e., the presence of animals and ceiling obstructions was not considered.

Model Chamber

Rather than conducting expensive tests on an actual building, a scale model was used. A chamber previously used for testing air inlets was renovated for use as a one-half scale model, an end view is shown in figure 1.

The length of the model building section is 4.06 m (13.3 ft), which is long enough to ensure two-dimensional airflow for the test conditions (Forthmann, 1934, as referenced in Adre and Albright, 1994). The walls and ceiling are of frame construction with a drywall interior. Plexiglass windows are mounted on three walls for observation and three access doors are provided on one end. Since data acquisition equipment must pass through the center aisle, the pit ventilation duct was split into two separate ducts, which meet at a fan plenum at the end of the chamber.

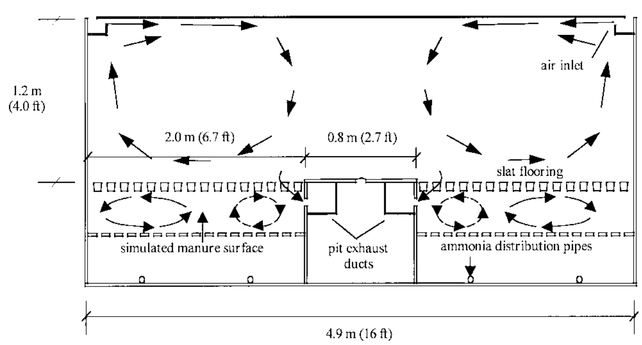


Figure 1–End view of the model chamber. Slat orientation shown defined as perpendicular to predominant airflow.

Ventilation System

Fresh air enters the room through adjustable side-wall slot inlets (see fig. 1) and is exhausted from the building by the pit ventilation system. The inlets were constructed of plywood with a sharp-edged orifice design. The inlet design was tested in a fan testing chamber to determine its airflow performance at various static pressures; a detailed description of the testing chamber may be found in Shahan (1985). The inlet was tested with three replications at four slot heights (3.18 mm to 12.7 mm) and twelve pressures (9.95 Pa to 64.7 Pa). From a general linear model analysis in the Statistics Analysis Software (SAS) program, a curve was fit to the data:

Table 1. Model airflow characteristics

Ventilation Treatment	Airflow (m^3/s)	Slot Height (mm)	DP (Pa)	Inlet Velocity (m/s)	Inlet Re	Inlet R_M (m^2/s^2)	ACH*
1	0.11	3.2	14.9	4.1	871	0.013	16
2	0.19	9.5	7.5	2.4	1530	0.013	28

* Air changes per hour.

$$\frac{Q}{L} = 0.3982 \times \left(h_i\right)^{0.836} \times \left(\Delta P\right)^{0.515} \quad (1)$$

where

Q is the airflow in m^3/s per meter of inlet length (L),

ΔP is the pressure drop through the inlet in Pa, and

h_i is the slot height in meters.

Two ventilation treatments were used for this experiment, both intended to be representative of winter design conditions. Ventilation rates were determined for the prototype building and scaled for the model. However, not only the ventilation rate needs to be scaled, it is also necessary to ensure that the airflow patterns are similar. At the time of this study, a number of criteria for airflow similarity had been proposed. For this research, the Jet Momentum Ratio (Rm) was used (Adre and Albright, 1994):

$$R_M = \frac{u_i^2 \times h_i}{\left(L + H\right)} \quad (2)$$

where u_i is the average inlet velocity, h_i is the inlet slot height, 2L is the total width of the building cross-section, and H is the height of the room. Table 1 details the airflow characteristics in the model. For the similar chamber in Adre and Albright's (1994) experiment, the threshold R_M was 0.012 ± 0.002 m^2/s^2; the R_M values for this experiment were in agreement.

The airflow rate into the chamber was measured using a differential manometer (Model 25, Dwyer Instruments, Inc.) across the inlets and calculated using equation 1. To obtain the desired pressure operating points, the pit exhaust fan was regulated by a variable speed controller (Model 3AB, Dayton Electric Mfg. Co.).

Pit Ventilation System

The pit ventilation system exhausts air from the building through ducts located under the center aisle (see fig. 2a). In order to allow room for data acquisition equipment, two ducts were used and were joined at a common annex at one end of the room. A variable speed centrifugal exhaust fan is located at the bottom of the annex. Figure 2 shows a side view and detail of the pit ventilation construction.

The number of exhaust holes in the ducts was estimated from design data in MWPS (1987). The spacing and size of the exhaust holes in the model were specified using the design method of Bloome et al. (1980). A total of six 4.5 cm (1.75 in.) holes were drilled in each duct, spaced 66 cm (26 in.) apart. The first hole was 38 cm (15 in.) from the fan end of the duct. To reduce entry losses, each intake hole was lined with duct tape. The ducts were also sealed with weatherstripping and tape to minimize leakage. A large duct cross-section was chosen to minimize friction loss, which has the additional advantage of making it easier to maintain uniform airflow within a reasonable range of ventilation rates.

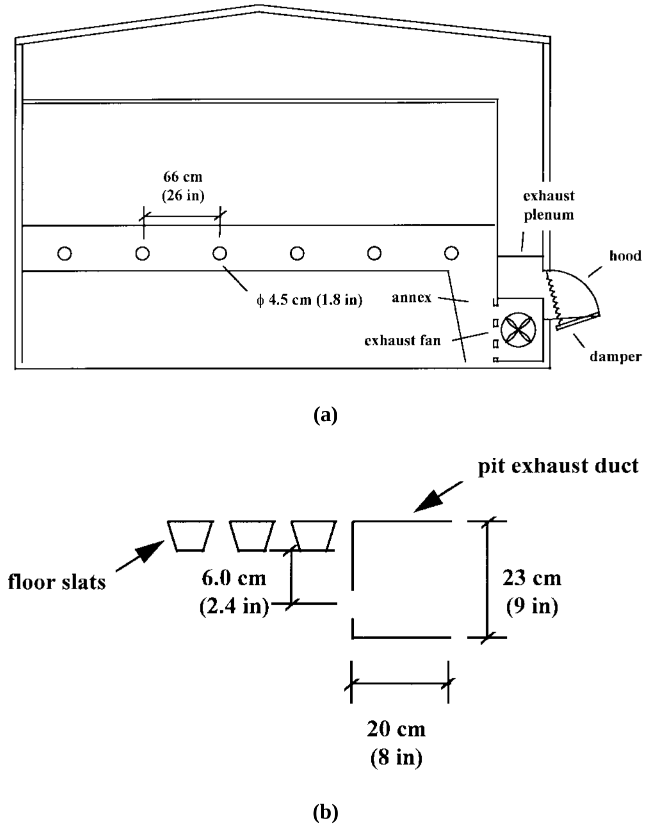


Figure 2–(a) Side view of pit ventilation construction, (b) detail of pit ventilation duct.

Slat Orientation

Two slat-orientations parallel and perpendicular to the predominant airflow pattern were used in the experiment. The prototype concrete slats were sized for growing pigs and geometrically scaled for the model; dimensions are based on data from MWPS (1991). A 1.3-cm (0.5-in.) slot width was used in the model. To reduce cost and weight, the slats in the model were constructed of foam insulation and supported by a wood frame.

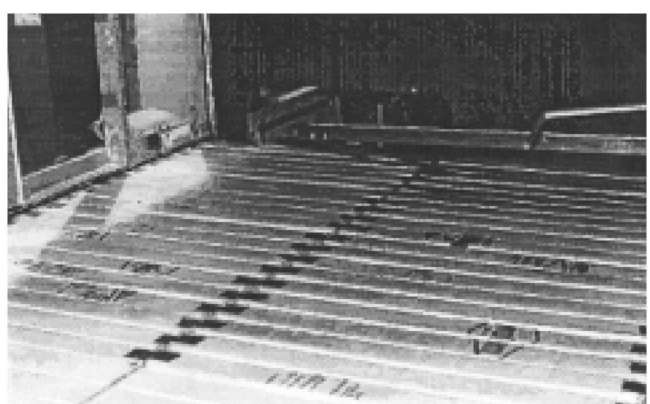


Figure 3–Slatted flooring in the chamber.

The slats were built in 1.02-m (40.0-in.) square sections with plywood end supports, making it easy to change the orientation of the flooring. The two slat orientations are identified in terms of the orientation relative to the predominant airflow pattern shown in figure 1. The floor as it was installed in the chamber is shown in figure 3.

GAS PRODUCTION

To simulate ammonia production from the manure surface in the pit, gaseous ammonia was supplied to the pit area of the model. Actual ammonia was chosen for this experiment due to the lack of an acceptable alternative. It is possible that there may be regions of stagnant air below the slatted floor where diffusion would be the dominant gas transport mechanism. Therefore, a substitute gas must possess diffusion characteristics similar to ammonia. The only alternative gas that was not highly flammable was water vapor, which would have been very difficult to control.

The ammonia distribution system is illustrated in figure 4. A perforated surface constructed of varnished 12.7-mm (0.5-in.) plywood sections with uniformly spaced 1.3 cm (0.5 in.) holes was used to create a uniform distribution surface for simulating ammonia release from a manure surface. This surface could be moved vertically on the floor support frame to change the depth of the simulated manure in the pit. The gas flux was kept at a constant value for all experimental treatments.

The ammonia gas was supplied from a pressurized tank of anhydrous ammonia and distributed to four lines at the bottom of the manure pit (see fig. 4). Each line had its own flowmeter with a valve to balance out the flow. Ammonia was regulated from the tank at a pressure of 276 to 345 kPa (40 to 50 psi) and a flow rate of 1.25 L/min (0.625 L/min to each pit in the model building).

Each of the four gas distribution lines was connected to a 1.9 cm inside diameter (0.75 in.) perforated PVC tube to ensure uniform distribution of the ammonia beneath the simulated manure surface, as shown in figure 4. Each tube ran the length of the chamber. Smoke testing indicated uniform distribution along the length of the tube.

For this experiment, two pit depth treatments were applied: a full pit and a nearly empty manure pit. A full pit was represented by a manure surface 10 cm (3.9 in.) below the bottom of the slatted floor; for a nearly empty pit, the manure surface was 50 cm (19.7 in.) below the slatted floor. For the prototype, this corresponds to head-space depths of 0.2 m (0.66 ft) and 1.0 m (3.3 ft).

To verify that the ammonia was uniformly distributed over the simulated manure surface, non-buoyant titanium tetrachloride (TiCl) smoke was introduced under the simulated manure surface and observed through windows at the end of the chamber. Results for both simulated manure depths showed that the perforated plywood surface was creating a back pressure effect on the gas below it, causing it to spread out over the surface in a uniform manner.

Ammonia concentrations checked at both sides of the chamber indicated symmetrical gas profiles. Determined from initial testing, the time allowed for ammonia distribution to stabilize in the chamber (once the gas supply was initiated) was two hours.

DATA ACQUISITION SYSTEM

Ammonia was measured in the chamber and in the exhaust stream. Ammonia levels in the chamber were measured with an electrochemical sensor (Model 54-1808-DL; Biosystems, Inc.); expected accuracy was ± 1 ppm with a 1-min response time. The electrochemical ammonia sensor was calibrated before and after each experimental run.

Ammonia concentrations in the chamber were measured at various locations. The sensor was positioned using a three-axis motion control system connected to an IBM compatible computer; a detailed description of the automated positioning system may be found in Wu (1994). Ammonia levels in the chamber were sampled at 10 Hz; values were recorded every 15 s for a total sampling period of 7 min. The first 2 min were not used, to account for the worst-case response time of the instrument.

Two regions; the animal occupied zone (AOZ) and the human occupied zone (HOZ), were investigated. AOZ in the prototype was defined as 25 cm above the floor, and in the model corresponds to 12.5 cm. HOZ in the prototype was defined as 1.5 m above the floor, or 0.75 m in the model (fig. 5). A total of 36 points in the AOZ and HOZ were sampled for each treatment run; the location of samples is shown in figure 5. Since airflow in the room was essentially two-dimensional, ammonia concentrations were sampled in a two-dimensional vertical plane perpendicular to the inlets. Due to symmetry, only one side of the room was sampled. The six columns of points were spaced 50 cm (20 in.) apart, except for the column closest to the wall, which was 14 cm (5.4 in.) from the wall. The rows of sampling points near the floor were spaced 5.0 cm (2.0 in.)

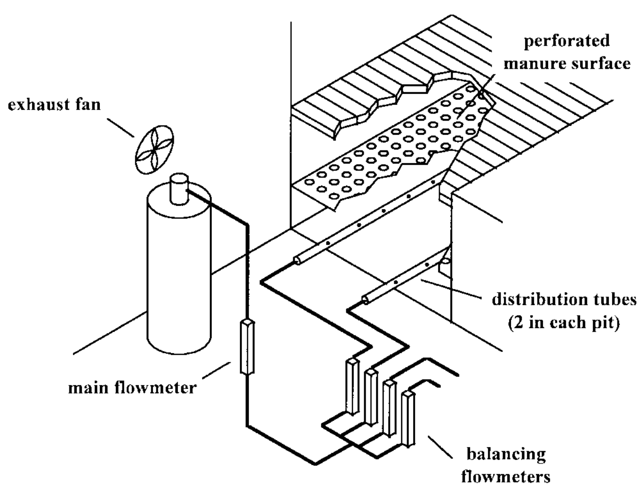


Figure 4–Ammonia distribution system.

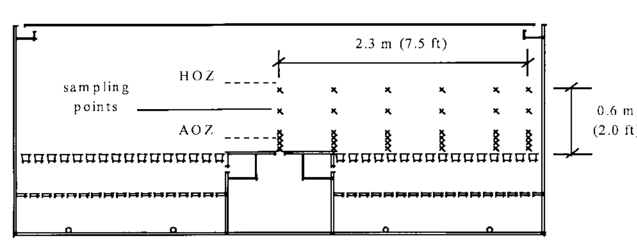


Figure 5–Sampling locations. AOZ and HOZ in model defined as 12.5 cm and 0.75 m above floor, respectively (i.e., 25 cm and 1.5 m in the prototype).

Table 2. Experimental treatments

Factor	Treatment (1)	Treatment (2)
Ventilation rate (V)	0.11 m^3/s	0.19 m^3/s
Head space depth (P)	10 cm	50 cm
Floor slat orientation (F)	Parallel to airflow	Perpendicular to airflow

apart, starting 5.0 cm (2.0 in.) above the floor. The top two rows were spaced 20 cm (7.9 in.) apart.

The experimental design was a 2 × 2 × 2 factorial with two replications for each of the eight treatments, resulting in a total of 16 experimental runs. Table 2 summarizes the experimental treatments.

RESULTS

AVERAGE EFFECTS

To determine the effect of the three factors on average ammonia levels in the model, the data collected were averaged for each treatment and compared using statistical methods. The data included all the locations sampled within the occupied zones in the chamber and the exhaust levels measured for each replication.

All of the ammonia concentration samples taken inside the chamber airspace were averaged for each treatment and are shown in table 3. Average ammonia levels were two to eight times higher at the low ventilation rate compared with the high ventilation rate. A nearly empty manure pit (50 cm) resulted in ammonia concentrations three to eight times higher than those for a full pit. While there was little difference between floor orientations at the 28 ACH and 10 cm treatments, a perpendicular slat orientation nearly doubled the ammonia levels in the occupied zone as compared with the slats oriented parallel to the predominant airflow pattern at the 50 cm treatment. However, the standard deviation for the F2 treatment (see table 3) at 28 ACH and 50 cm is fairly high when compared with the other data.

To determine the statistical significance of these differences, an analysis of variance was used. Table 4 shows the results of an ANOVA for main effects.

Table 3. Average ammonia values (ppm) for each treatment*

Airflow (V)	Head Space (P)	Slats Parallel (F1) (ppm)	Slats Perpendicular (F2) (ppm)
16 ACH	10 cm	8.7 (3.3)	5.5 (1.5)
16 ACH	50 cm	25.0 (7.7)	24.4 (8.6)
28 ACH	10 cm	1.1 (0.3)	1.4 (0.4)
28 ACH	50 cm	5.1 (1.8)	11.1 (6.3)

* Average of 72 data points per entry; standard deviations in parentheses.

Table 4. ANOVA for main effects using all treatments

Source	DF*	SS†	MS‡	F§	α
V	1	18286	18286	542.67	< 0.001
P	1	21533	21533	639.04	< 0.001
F	1	52	52	1.54	> 0.05
Error	572	19274	34		
Total	575	59145			

* Degrees of freedom.
† Sum of squared differences.
‡ Mean squared differences = SS/DF.
§ F-statistic = MS/MS.

Ventilation rate ($\alpha < 0.001$) and pit depth ($\alpha < 0.001$) were both significant while slat orientation ($\alpha > 0.05$) was not, likely due to the high standard deviation for slat orientation.

An ANOVA for main effects and interactions was performed separately for each ventilation treatment. At the low ventilation rate (16 ACH), both pit depth and slat orientation were significant ($\alpha < 0.01$) but their interaction was not ($\alpha > 0.05$). However, at the high ventilation rate (28 ACH), pit depth, slat orientation, and their interaction were all found to be significant ($\alpha < 0.001$). This supports the possibility that the slat orientation had an effect at a high ventilation rate with a nearly empty pit, as suggested with the results in table 3.

EFFECT OF VENTILATION RATE

Although considerably affecting average levels of ammonia in the occupied zones, the ventilation rate does not appear to significantly affect the spatial distribution of ammonia in the airspace above the floor (fig. 6). Essentially, an increase in ventilation rate serves the purpose of entraining and removing contaminants at a higher rate, thus reducing the levels of ammonia in a given volume of air. A higher ventilation rate, however, did not create a substantial change in the airflow patterns across the slat orientation and manure depth treatments. This conclusion is supported by the similarity of momentum ratio (R_M) numbers for the two ventilation treatments, which implies that airflow patterns should be similar.

EFFECT OF MANURE DEPTH

The results shown in figure 6 indicate there may be differences in concentration gradients in the occupied zones between manure depth treatments. Differences can be observed at both the high and low ventilation rates. At the low ventilation rate, the location of the peak ammonia concentration varies with manure depth, as shown in figures 6a, b, and c. For the full manure pit, ammonia levels reach their highest levels at approximately $x/L = 0.41$ and do not change appreciably along the remaining distance to the wall. For a nearly empty manure pit at the low ventilation rate, ammonia concentrations do not rise until approximately $x/L = 0.61$, at which point the peak levels are found. In the remaining distance to the wall, ammonia levels immediately above the floor ($y/H = 0.04$) sharply decrease to levels found at the other y/H locations. Ammonia concentrations at y/H locations greater than 0.04 follow a similar trend to that observed at $y/H = 0.04$, but in a much weaker form, essentially leveling off after the peak point at $x/L = 0.61$.

EFFECT OF FLOOR SLAT ORIENTATION

An observation of figure 6 provides little indication of slat orientation effects on spatial variability or average ammonia levels in the occupied zones, with the exception of the slats oriented perpendicularly to the airflow at the 28-ACH and 50-cm treatment levels. Although there is no datum to explain the difference in average ammonia levels, it is possible that the orientation of the slats affects the degree of air exchange between the head-space and the occupied zones at a high ventilation rate.

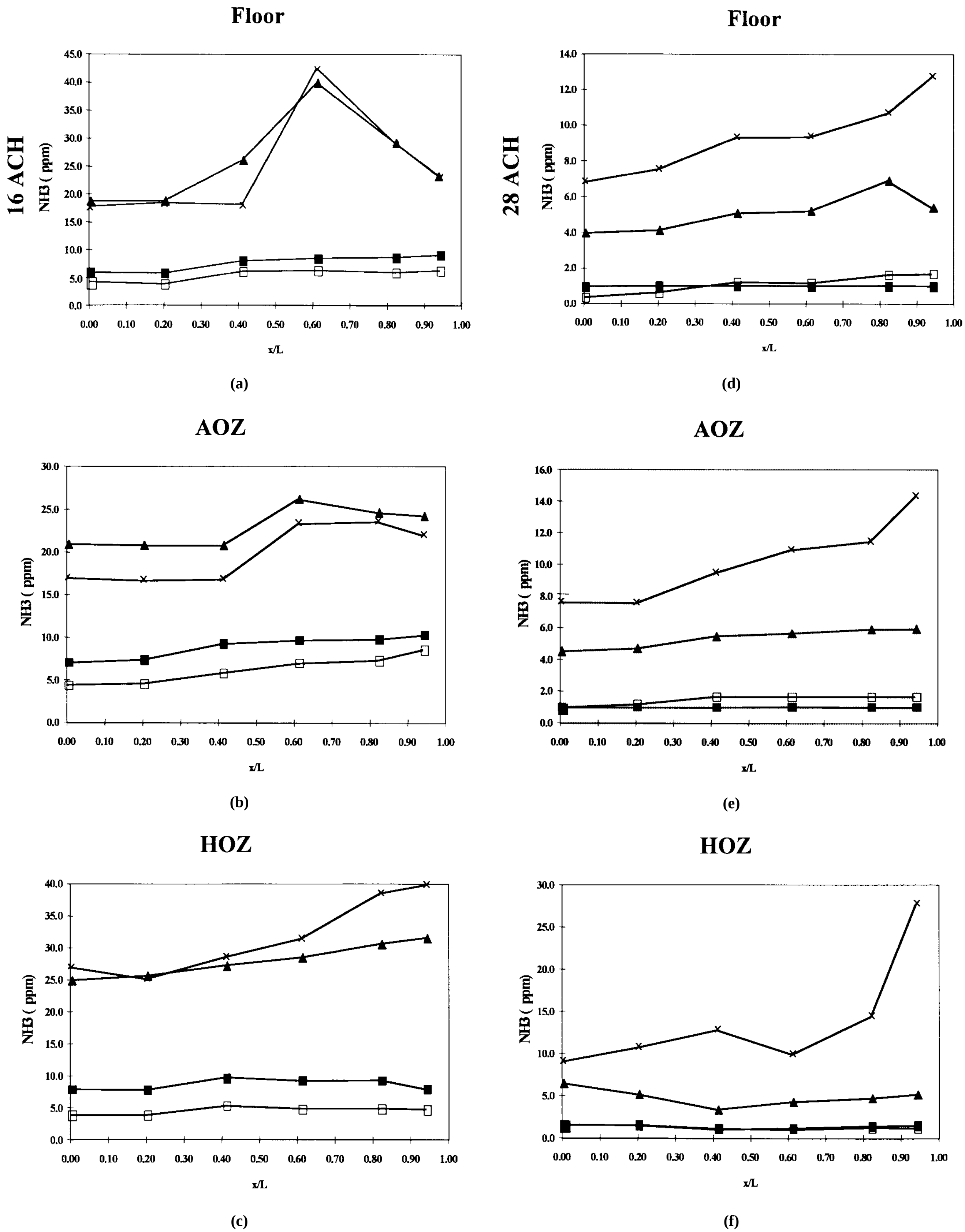


Figure 6–Ammonia distribution as a function of distance (x/L) from building center and treatment level; where ■ = 10 cm head space and parallel slats, □ = 10 cm head space and perpendicular slats, ▲ = 50 cm head space and parallel slats, × = 50 cm head space and perpendicular slats. Floor measurements at y/H = 0.04, AOZ measurements at y/H = 0.10, and HOZ measurements at y/H = 0.50.

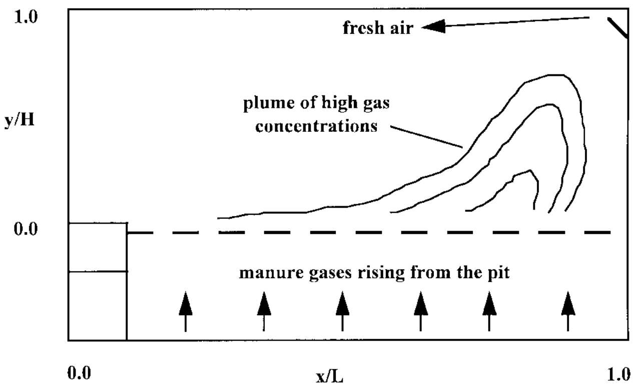


Figure 7–The plume effect.

DISCUSSION

The ammonia concentrations near the wall were typically 1.5 to 2 times higher than those at the center of the building. The trend of increasing ammonia levels from the center of the building to the wall can be explained on a physical basis. As a consequence of the rotary airflow illustrated in figure 1, a given volume of air at the center of the room will travel across the floor towards the wall, entraining rising manure gases as it moves. The additive effect of the gas entrainment will result in higher ammonia levels in the same volume of air near the wall. Since the airflow is rotary, air approaching the wall will rise toward the ceiling, creating a plume of contaminated air, as illustrated in figure 7.

To gain a better understanding of the transport phenomenon taking place in the airspace, smoke testing using a non-buoyant TiCl source was performed for the two pit depth treatments at the low ventilation rate. Only the parallel slat orientation was tested. The smoke testing was a valuable tool for visualizing contaminant movement both above and below the slatted floor. Figure 8 consists of photographs of the results.

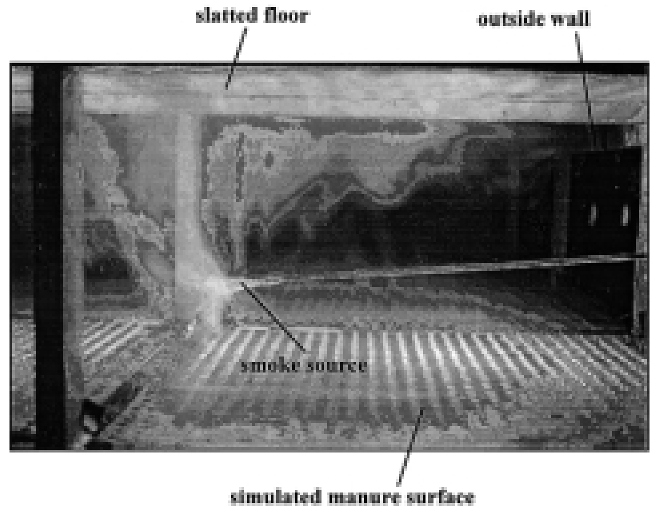
The most striking differences were observed in the head-space region. For the full manure pit, smoke rising from the manure surface moved towards the exhaust holes, indicating the presence of a potential flow region below the floor. This effect was less pronounced near the wall, where smoke was observed to rise up through the slats.

For the nearly empty manure pit, no potential flow was observed. Smoke was evenly distributed in the head-space below the slatted flooring, as shown in figure 8a. No apparent interaction with the occupied zone airflow patterns was observed below the floor for this treatment.

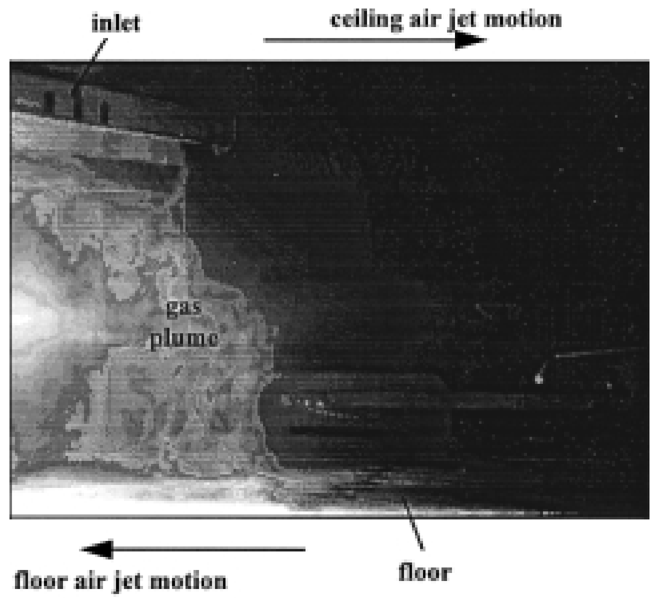
Differences were also observed above the floor in the occupied zones. For both manure depths, a plume effect was very evident near the outside wall (see fig. 8b). However, the plume was much larger and more concentrated for the nearly empty manure pit, concurring with the higher ammonia levels measured for this treatment.

For a nearly empty manure pit, there is little stratification of ammonia in the head-space, and there would be a nearly constant concentration gradient along the length of the slatted floor. In this case, the plume effect illustrated in figure 7 would result in fairly large horizontal and vertical concentration gradients, as observed in figure 6.

A limitation of this study is the use of an isothermal model with no consideration of ambient effects on gas production. Although it appears that a duct flow situation above the manure surface reduces ammonia levels in the occupied region for this study, it also increases air velocities above the manure surface. Increasing air velocities above the manure surface has been shown to increase ammonia release (Anderson et al., 1987; Zhang et al., 1994); therefore, the benefits of duct flow observed for this experiment may be reduced in an actual application due to higher ammonia levels in the head-space and the resulting higher concentration gradients. In addition, ammonia release rates will vary over time as the manure pit fills up (Zhang, 1994).



(a)



(b)

Figure 8–(a) Smoke movement in the headspace for a nearly empty manure pit, V1 and F1 treatments; (b) smoke movement in the occupied zones for a full manure pit, V1 and F1 treatments.

One way to prevent the exit of contaminated air from the head-space is to create an adequate pressure drop across the entire surface of the slatted floor. To maintain a minimum velocity at the manure surface, the airflow rate must be sized for the volume of the head-space. An advantage of this approach is that a less expensive annex pit ventilation system could be used. Gustafsson (1987) found that a minimum flow rate with a negative pressure of approximately 0.25 to 0.5 Pa (0.001 to 0.002 in. w.c.) in the head-space of a shallow pit with annex ventilation prevented upward motion of air from the pit and created even exhaustion over the floor surface. However, Gustafsson's (1987) study was performed in a barn with a partially slatted floor and a relatively small manure pit.

Ventilation requirements based on the above guidelines for a totally slatted floor with a deep manure pit are prohibitive, especially in the winter when supplemental energy is a cost concern. Also, varying the ventilation rate based on manure depth could require the use of additional controls, adding expense and maintenance to increasingly complex agricultural ventilation systems.

A reasonable approach may then be to reduce or eliminate upward air motion from the head-space to the occupied zones. This may be achieved by a floor design that is restrictive enough to create an adequate pressure drop without requiring an unacceptable increase in fan capacity and energy use. Of course, the original intent of the slatted floor must be maintained to permit easy transfer of animal wastes to the storage pit below while providing a comfortable floor environment for the animals. In addition, excessive drafts at the floor surface must be avoided, particularly in nurseries.

In the event that it is not possible to design a fully effective localized exhaust system for the manure pit, the alternative is to maintain a ventilation rate that achieves adequate dilution of contaminants. This requires that the production rate of ammonia be known in order to complete the mass balance for the building airspace, and may require ventilation rates higher than those currently used to control humidity and carbon dioxide levels. Therefore, if an effective localized exhaust system can be designed, the added expense in construction may be offset by savings in energy due to a comparatively lower ventilation rate.

CONCLUSIONS

A study was performed on the effects of building design and management factors on ammonia levels and distribution in a one-half scale model section of a pit-ventilated swine confinement building. The pit ventilation system utilized a perforated duct design located under a center aisle. Ammonia production from the manure surface in an under-floor pit was simulated under isothermal conditions, with no floor or ceiling airflow obstructions present. Average levels of ammonia and spatial distribution within the occupied zones were compared, including two ventilation rates representative of winter conditions, two slat orientations and two manure depths.

A number of conclusions can be made regarding the effects of ventilation rate, floor type and manure depth on average levels and spatial stratification of ammonia in the model building:

1. Increasing the ventilation rate by a factor of 1.8 from 0.106 m^3/s to 0.186 m^3/s (225 m^3/s to 395 m^3/s) reduced average levels of ammonia in the occupied zones by factors ranging from 2 to 8.
2. Average ammonia concentrations in the occupied zones for a full manure pit were lower than those for a nearly empty manure pit by factors ranging from 3 to 8.
3. The orientation of the floor slats did not have a significant effect on average ammonia levels in the occupied zones, with the possible exception of the case of a high ventilation rate and a nearly empty manure pit when all tests were combined. Floor slat orientation did not noticeably affect ammonia distribution in the occupied zones, except for the case of a high ventilation rate and a nearly empty manure pit.
4. Average ammonia concentrations at a high ventilation rate with a nearly empty manure pit were nearly doubled for a slat setting perpendicular to the predominant airflow direction when compared with slats parallel to the airflow.
5. There was a general trend of higher ammonia concentrations near the outside wall for the side wall slotted inlet ventilation system used in this study. Ammonia levels near the wall were typically 1.5 to 2 times higher than those at the center of the room as a result of a plume effect created by the dominant airflow patterns in the building.
6. Increasing the ventilation rate did not, in general, change the distribution pattern of ammonia across the floor and manure depth treatments. Increasing the ventilation rate increases dilution of ammonia in the occupied zone and the magnitude of the potential flow found in the head-space for a full manure pit, but did not appreciably affect observable air motion in the head-space for a nearly empty manure pit.
7. Horizontal stratification was increased for a nearly empty manure pit at the low ventilation rate; a distinctive peak in ammonia concentration was found at a point $x/L = 0.61$ for a nearly empty manure pit as compared with a slowly increasing gradient starting at $x/L = 0.41$ for a full manure pit. Smoke testing indicated a larger contaminant plume for a nearly empty manure pit as compared with a full manure pit. The difference is possibly due to the influence of potential flow in the head-space for a full manure pit, which creates higher ammonia levels near the exhaust duct in the center of the room. This creates a concentration gradient in the head-space that increases towards the center of the building, counteracting horizontal stratification due to the plume effect.
8. Large stagnant regions observed in the head-space, particularly for a nearly empty manure pit, indicate that it is necessary to use ammonia or a gas with similar diffusion characteristics to accurately simulate the movement and distribution of ammonia in swine confinements with under-floor manure pits.

Future Work

The data presented in this research suggest several areas that need further investigation. Further study of manure depth in the pit, including intermediate levels, may allow a determination of a pit depth criterion for the creation of sustained potential flow regions in the head-space. The effect of floor type and its interaction with head-space volume in enhancing manure gas removal from the head-space should be examined in further detail, including additional floor designs and sizes.

Since diffusion in the head-space seems to be an important mechanism of ammonia transport, future computer modeling efforts may aid in a better understanding of the gas transport phenomenon at work in stagnant regions of a confined space. Environmental factors that may be important in the contaminant transport process include temperature and humidity effects due to the presence of animals in the building.

Factors not considered in this experiment that will certainly affect ammonia distribution and possibly the effectiveness of pit ventilation include the inlet location and design, and the amount of slatted floor and manure pit area. These should be considered in future experiments because there is a fairly wide variety of building designs in use in the swine industry today.

Future studies of ammonia distribution should bear in mind the diffusion characteristics of the simulation gas; "safe" gases such as carbon dioxide may not accurately represent actual gas concentrations for ammonia. In addition, it is important to use reliable measurement methods and accurate ventilation control to reduce experimental uncertainty. The ammonia introduction system needs to be improved to prevent suction effects through the simulated manure surface while providing a uniform gas flux.

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