

Development and Validation of 3-D CFD Models to Simulate Airflow and Ammonia Distribution in a High-Rise™ Hog Building during Summer and Winter Conditions

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ABSTRACT

Swine confinement buildings typically store manure in deep pits or use flush systems that generate liquid manure. This liquid is of great concern to hog producers because of its' potential environmental impacts, odors and effects on human and animal health. An alternative system, the High-Rise™ Hog Building (HRHB) attempts to address these issues by drying and partially composting hog manure *in situ*. However its ability to maintain optimal air quality throughout the animal space is unclear. In this study, 3-dimensional isothermal CFD models were developed to simulate the airflow patterns and ammonia distribution within a commercial High-Rise™ Hog Building (HRHB) during high ventilation rate (summer) and low ventilation rate (winter) operating conditions using FLUENT®, a computational fluid dynamics program. The models were validated by measuring ammonia concentrations at 8 positions and two elevations on at least 2 different occasions within an HRHB building after finished hogs were removed. The CFD model predicted ammonia concentrations were not significantly different than the measured median 4-hour ammonia concentrations under both summer and winter conditions. This indicated that CFD modeling could be an effective way to evaluate air quality and ventilation across the 3-D space of a HRHB. A simulation using the initial and boundary conditions determined when hogs were present showed that in winter some ammonia from the manure storage area flows into the pig space which may affect animal health. According to the simulation, under winter conditions, ammonia concentrations within the pig space as high as 29 ppm were predicted at a height of 1.2 m (4 feet). Pens furthest from the exhaust fans exhibited the greatest ammonia concentrations. Under summer operating conditions, ammonia concentrations in the pig area were more evenly distributed and predicted to be below 1.5 ppm throughout the hog area and well below levels that are considered to adversely affect animal health. These ammonia concentrations are similar to the ranges previously observed in conventional deep pit buildings.

Keywords. Computational Fluid Dynamics (CFD), High-Rise™ Hog Building (HRHB), Ammonia, Air quality, Ventilation.

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INTRODUCTION

Swine producers have become increasingly aware of environmental issues associated with production, storage and utilization of liquid hog manure. In order to minimize or eliminate the storage of liquid manure, new technologies are being developed where manure is stored as a solid (Humenik et al., 2002; Williams et al., 2002). The High-Rise™ Hog system (HRHB) is a hog finishing system in which manure is composted *in situ*. Manure falls through a slatted floor onto a bed of bulking agents (wood shavings, sawdust, straw, ground pallets, etc.) while air is forced up through the manure/bedding mix via an in-floor aeration system leading to drying and partial composting (Keener *et al.* 2001; Mescher *et al.*, 1999; Michel et al., 2001; Stowell et al., 1999). Ventilation fans are located in the sidewalls of the lower story of the building. Fresh air is drawn into the pig space through a baffled ceiling inlet and down into the lower story, where it is exhausted with the air used to aerate the manure mix (Figure 1). The purpose of using this mechanical aeration and ventilation system is to dry the manure/bedding mix, promote composting and maintain optimum air quality in the animal space.

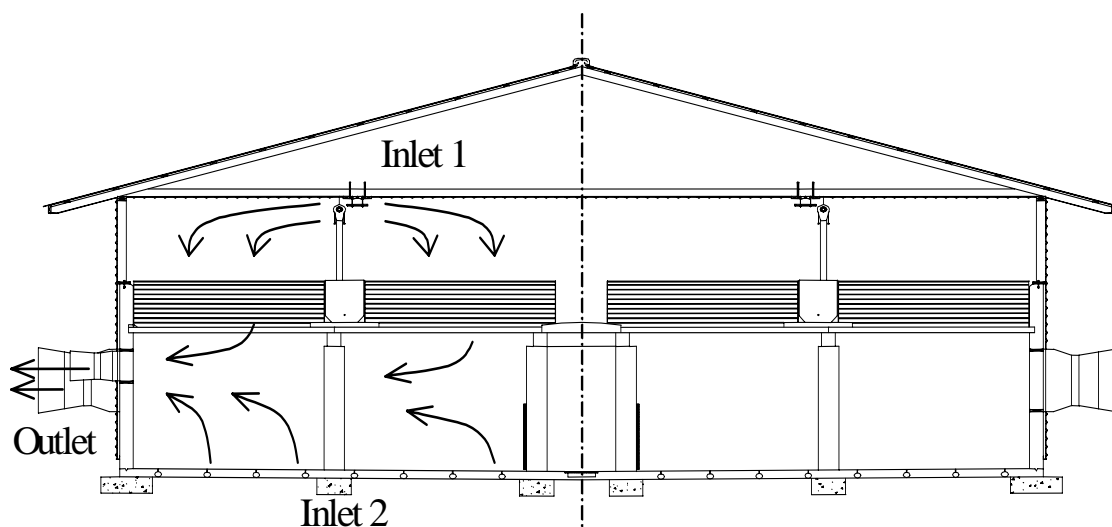


Figure 1. Cross section of a High-Rise™ hog building in Darke County, Ohio.

An important issue with hog finishing buildings is the effect of in-house manure storage on building air quality. Various studies have been done to evaluate the air quality in swine buildings and investigate the performance of mechanical aeration and ventilation systems. As one of the main toxic gases generated by animal waste (Jones et al., 1998; Heber, 1990), ammonia has been studied in great detail. Koerkamp et al. (1998) reported that the average ammonia concentrations in different houses for finishing swine in Northern Europe were from 5 to 18 ppm with momentary peak levels over 50 ppm. A preliminary study of a HRHB found that ammonia concentrations were below 20 ppm in the upper pig space throughout the year and below 40 ppm in the lower story during most months of the year (Keener et al., 2001; Stowell et al., 1999 & 2000a). However, over some weeks in winter during periods of minimum ventilation, ammonia levels reached as high as 80 ppm in the manure pit area. Stowell *et al.* (2000a) also studied the

ammonia emission from the HRHB. They found that the average ammonia concentrations within the exhaust air from HRHB ranged from 12.6 ppm to 18.5 ppm. However, measurements for all of these studies were taken at only a few locations and information about the distribution of ammonia throughout the building was limited. Ammonia concentrations in excess of 30 ppm in the pig space were also detected during the minimum ventilation period in winter (Sun, 2002). These levels were higher than the threshold limit value (TLVs) of 25 ppm, over which hog's somatic growth is depressed (Gustin et al., 1994), the level of 10 ppm recommended by Sweden regulations to protect stockman welfare (Koerkamp et al., 1998), and the exposure limit of 7 ppm suggested by Donham and his colleagues considering the synergistic reaction of combined mixture of dust and gases (Donham, 1993 & 1999; Donham et al., 1989 & 1986). Thus, a better understanding of ammonia distribution in hog buildings is needed. Models of ammonia distribution throughout the pig space may help to evaluate air quality throughout the entire volume of a HRHB and allow improvements in building design to be tested prior to construction modifications.

CFD modeling has been widely used to study airflow in green houses and animal buildings (Lee & Short, 2000; Wu & Gebremedhin, 2001; Quinn and Baker, 1997; Jackson *et al.*, 1999; Harral *et al.*, 1997; Ayad, 1999; Bjerg *et al.*, 1999, 2000, 2001 & 2002; Svidt *et al.*, 1998; Sun *et al.*, 2002). Sun et al., (2000) developed a two-dimensional Computational Fluid Dynamics (CFD) model to investigate air quality and ventilation conditions and to predict airflow and ammonia concentrations throughout a HRHB. Because the air velocity ranges across both laminar and turbulent flow regimes, both laminar and turbulent CFD models were used to predict airflow and ammonia distribution in a High-Rise™ Hog building (Sun et al., 2002). Airflow patterns measured using anemometry and ammonia concentrations within an experimental HRHB were compared to model generated data (Keener *et al.* 2001; Stowell *et al.* 1999; Stowell *et al.* 2000b). Both models predicted the highest ammonia concentration in the pig space was near the center of the pen, not near the walkway where previous measurements had been made. However, 2-dimensional CFD models are limited by their representation of real building geometry and processes such as fan placement and ammonia distribution across the horizontal area of the animal space (Figure 2). To overcome these limitations, 3-dimensional CFD models are needed for better prediction of airflow characteristics and ammonia concentrations in HRHBs.

The objectives of this study were (1) to develop 3-dimensional CFD models of airflow and ammonia distribution in a High-Rise™ Hog Building; (2) to validate the 3-dimensional CFD models using ammonia concentration measurements in a full-scale HRHB, (3) to investigate the performance of the ventilation system in the HRHB in summer (high ventilation rate) and winter (low ventilation rate) conditions using CFD model simulations of the HRHB.

MATERIALS AND METHODS

CFD Numerical Modeling

To build a mathematical representation of a HRHB and numerically solve the Reynolds-averaged Navier-stokes equations over a discretized flow field based on the finite volume method, GAMBIT® and FLUENT® 5.4 CFD software (FLUENT Inc., Lebanon, New

Hampshire) were used. The Reynolds-averaged processes assume the instantaneous velocity could be written as a sum of its statistical average and the instantaneous deviation from that average. This assumption efficiently simplified the computational process (Bird, 1960; Brodkey, 1967). However, additional unknown variables such as instantaneous velocity components are introduced into these equations. Turbulence models were used to determine these variables in terms of known quantities. In Fluent[®] 5.4, several statistical turbulence models including Spalart-Allmaras model (Spalart & Allmaras, 1992), standard κ - ε model (Launder and Spalding, 1972), renormalization-group (RNG) κ - ε model (Yakhot *et al.*, 1986) and realizable κ - ε model (Shih *et al.*, 1995) are available for the different requirements (FLUENT, 1998). In this study, renormalization-group (RNG) κ - ε model was used to simulate the airflow in a HRHB in winter conditions because it provides an analytically derived differential formula for effective viscosity that accounts for low-Reynolds-number effects (FLUENT, 1998). The standard κ - ε model was used to simulate the airflow in summer (high ventilation rate) conditions. The Reynolds stresses were assumed to be proportional to the mean velocity gradients, with the constant of proportionality being the turbulent viscosity, μ_t , which is known as the Boussinesq hypothesis (Bird, 1960; Brodkey, 1967; FLUENT, 1998).

Close to solid walls, viscous effects are believed to predominate over turbulent effects (FLUENT, 1998). Wall functions used by Launder and Spalding (1974) were applied in conjunction with the RNG κ - ε equations. The walls were modeled as standard, solid walls in the FLUENT program (Patankar, 1981; FLUENT, 1998). In the upper story, the walls were assumed to be smooth with a roughness height of zero. In the lower story, a concrete roughness height of 0.5 mm and roughness constant of 0.5 were used.

The following assumptions were used in the development of the model. The system was assumed to be isothermal and no heat sources such as pigs, heaters or lights were considered. Energy balance equations were not included in the models since the system is typically operated under a controlled fixed temperature (Stowell, *et al.* 2000b). Furthermore, the gas phase was assumed to consist of a mixture of air and ammonia. The gas phase was simulated as an incompressible, continuous flow. No chemical reactions or dispersed phase transportation were assumed to occur in the computational domain. The computations were performed for steady state conditions.

With these simplifying assumptions, the governing equations including the RNG κ - ε turbulence model (Brodkey, 1967; FLUENT, 1998) were:
conservation of mass,

$$\frac{\partial}{\partial x_i}(\rho u_i) = 0 \quad (1)$$

conservation of momentum,

$$\rho \frac{Du_i}{Dt} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left(\mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \delta_{ij} \frac{\partial u_k}{\partial x_k} \right) - \rho \overline{u_i' u_j'} \right) + \rho g_i + F_i \quad (2)$$

conservation of species,

$$\frac{\partial}{\partial x_i}(\rho u_i m_i) + \frac{\partial}{\partial x_i}(J_{i,i}) = 0 \quad (3)$$

where u is velocity, μ is viscosity, ρ is fluid density, p is the static pressure, g_i is gravitational acceleration, m_i is the mass fraction of species i , $J_{i,i}$ is the diffusion of species i in the i direction, and F_i is external body force in the i direction. Here, F_i also contains other model-dependent source terms such as porous media sources.

The Reynolds stress (Brodkey, 1967; FLUENT, 1998) was

$$-\overline{\rho u_i' u_j'} = \mu_t \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{2}{3} \left(\rho k + \mu_t \frac{\partial u_j}{\partial x_i} \right) \delta_{ij} \quad (4)$$

κ is the turbulent kinetic energy. μ_t is the turbulent viscosity.

$$\mu_{eff} = \mu + \mu_t \quad (5)$$

μ_{eff} is the effective turbulent viscosity. It is computed as a function of κ and the dissipation rate of turbulent kinetic energy (ε). Under the minimum ventilation conditions, the Reynolds numbers in the building were relatively low (Sun, et al. 2002). μ_{eff} is achieved by solving the differential equation in the RNG model (FLUENT, 1998).

$$d \left(\frac{\rho^2 k}{\sqrt{\varepsilon \mu}} \right) = 1.72 \frac{\hat{v}}{\sqrt{\hat{v}^3 - 1 + C_v}} d\hat{v} \quad (6)$$

$$\hat{v} = \mu_{eff} / \mu ; C_v \approx 100.$$

In the high Reynolds number limit ($>5 \times 10^4$), this equation gives

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon}, \quad (6)$$

$$C_\mu = 0.0845.$$

In the summer condition, the Reynolds number at the ceiling inlet and outlet were 5×10^4 and 6×10^5 , respectively.

The value of κ and ε are obtained by solution of conservation equations.

$$\rho \frac{Dk}{Dt} = \frac{\partial}{\partial x_i} \left(\alpha_k \mu_{eff} \frac{\partial k}{\partial x_i} \right) + G_k + G_b - \rho \varepsilon \quad (7)$$

$$\rho \frac{D\varepsilon}{Dt} = \frac{\partial}{\partial x_i} \left(\alpha_\varepsilon \mu_{eff} \frac{\partial \varepsilon}{\partial x_i} \right) + C_{1\varepsilon} \frac{\varepsilon}{k} (G_k + C_{3\varepsilon} G_b) - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} - R \quad (8)$$

where α_k and α_ε are the inverse effective Prandtl numbers which are computed using the formula

$$\left| \frac{\alpha - 1.3929}{\alpha_0 - 1.3929} \right|^{0.6321} \left| \frac{\alpha + 2.3929}{\alpha_0 + 2.3929} \right|^{0.3679} = \frac{\mu_{mol}}{\mu_{eff}} \quad (9)$$

$$\alpha_0 = 1.0,$$

$\alpha_k = \alpha_\varepsilon \approx 1.393$ in the high Reynolds number limit ($\mu_{\text{mol}}/\mu_{\text{eff}} \ll 1$).

G_k (FLUENT, 1998) represents the generation of turbulent kinetic energy due to the mean velocity gradients, calculated by

$$G_k = \mu_t S^2 \quad (10)$$

where S is the modulus of the mean rate-of strain tensor, define as

$$S \equiv \sqrt{2S_{ij}S_{ij}} \quad (11)$$

$$S_{ij} = \frac{1}{2} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \quad (12)$$

G_b is the generation of turbulent kinetic energy due to buoyancy, which is negligible in the isothermal model. The R term is given by

$$R = \frac{C_\mu \rho \eta^3 (1 - \eta/\eta_0) \varepsilon^2}{1 + \beta \eta^3} \frac{1}{k} \quad (13)$$

where $\eta \equiv Sk/\varepsilon$, $\eta_0 = 4.38$, $\beta = 0.012$.

With this term, the RNG model is more responsive to the effect of rapid strain and streamline curvature than the standard k - ε model (Sun et al. 2002). The constants $C_{1\beta}$, $C_{2\beta}$ had the following values (FLUENT, 1998):

$$C_{1\beta} = 1.42, \quad C_{2\beta} = 1.68.$$

The governing equations were solved using measured initial and boundary conditions of the inlet airflow velocities and gas concentrations, the turbulence intensity and length scale, and the solid surface boundary conditions (Table 1).

HRHB Operational Conditions and Measurements

The dimensions and operating conditions of a commercial HRHB located in Darke County, Ohio (Sun et al., 2002) were used to generate the CFD model. This two-story building was 13.7 m wide, 71.1 m long and 7.72 m high. Each story had an indoor height of 2.44 m. Fresh air (without ammonia) enters the upper story of this building from the attic through a baffled ceiling inlet (Inlet 1 in Figure 1). It mixes with building air and moves down through the slatted floor to the lower story, which has a manure bed of 0.3 to 0.6 m (1-2 feet). Air is also blown into the building from below the bedding through the manure mixture via a fan and manifold system (inlet 2 in Figure 1). All air is exhausted through the outlets in the sidewalls of the lower story. The ventilation conditions vary under summer and winter conditions. Both conditions were investigated by changing the initial conditions and model used (see above). A representative section of the HRHB was simulated based on the geometrical arrangement of the exhaust fans (Figure 2 and 3). It was 6.7 m wide and 4.4 m high. The length was about 12 m for winter conditions and 5 m for summer conditions, respectively. Totally, more than 200,000 grid cells were used for each model of summer and winter conditions (Figure 4).

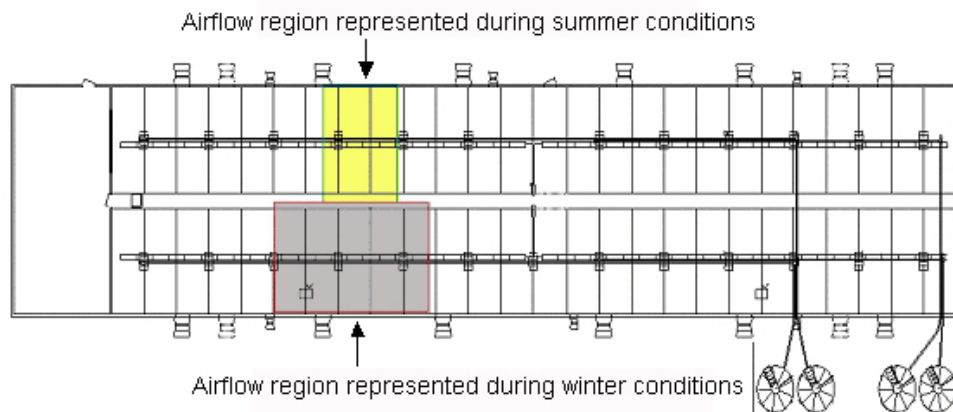


Figure 2. Modeled regions in the horizontal plane of a HRHB.

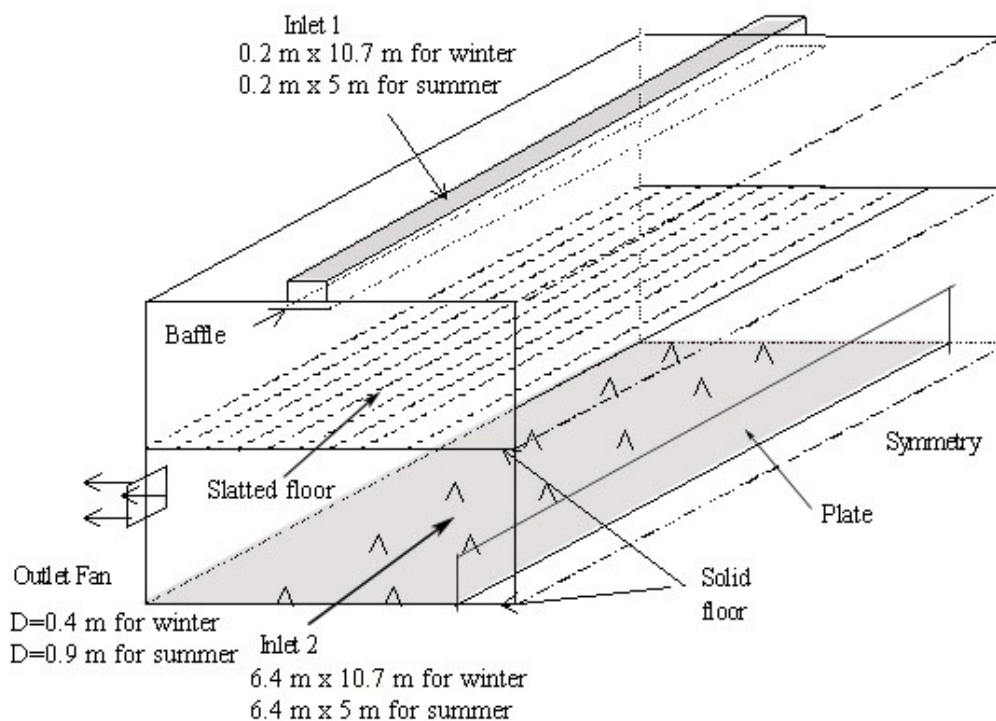


Figure 3. Building representation for modeling purposes and geometry used for CFD modeling for a High-Rise™ hog building.

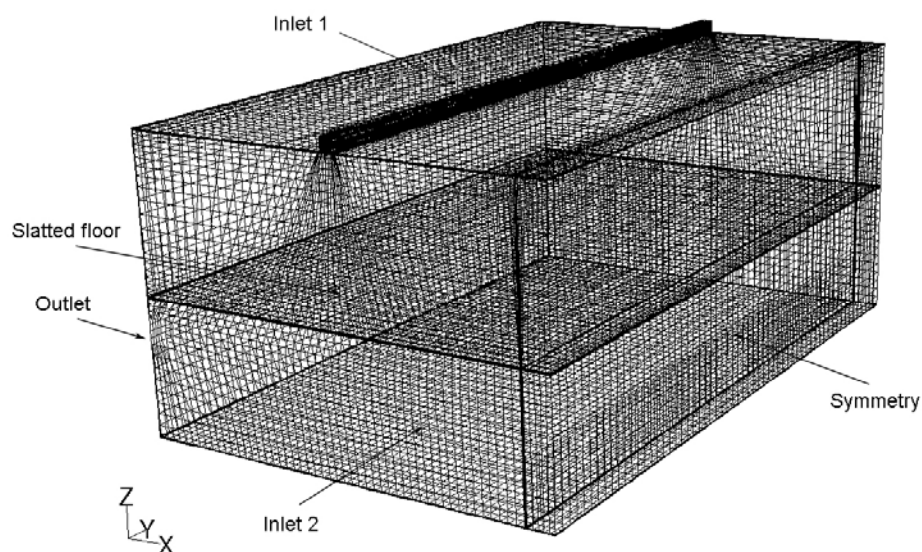


Figure 4. Grid used for computational fluid dynamic modeling of a High-Rise™ hog building (Winter conditions).

The slatted floor is 0.1 m thick and has slots of 2.5 cm (1 inch) every 18 cm (7 inches). It was simplified for modeling purposes as a porous media with a porosity of 0.14 (Fluent, 1998). The permeability was assumed to be 10^{10} m^2 and the inertial resistance coefficient was estimated to be 480 based on superficial velocity calculated based on the measured pressure drop through the slatted floor (FLUENT, 1998). No hogs were simulated in this model.

In winter, six small fans (0.406 m diameter) are used under the minimum ventilation condition to minimize heat losses from the building. Twelve more 0.914 m (diameter) fans are used for cooling in hot summer conditions. To measure airflow velocities at inlet 1, hotwire anemometers were used. The measured values were used as boundary conditions in the model (Table 1). A manometer was used to measure the pressure drop through the floor aeration system and calculate the floor air flow rate using a fan curve (Keener et al., 2001). The airflow velocities entering Inlet 2 were computed using the flow rate and manure bed area, which were also used as boundary conditions (Table 1). In the model, the airflow velocity profiles at Inlet 2 and Inlet 1 are considered to be uniform with a direction perpendicular to the inlet surface (Figure 3). The initial turbulent kinetic energy (κ) and dissipation rate of turbulent kinetic energy (ε) at the inlets were computed using the functions given by FLUENT (1998).

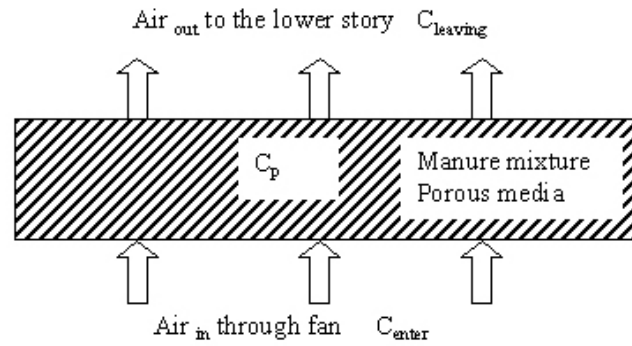
Table 1. The initial and boundary conditions used in the CFD models to simulate summer and winter conditions.

Property	Condition	
	Summer	Winter
Fan Diameter (m)	0.914	0.406
Gap size of the inlet baffle (m)	0.080	0.006
<i>Inlet 1 (ceiling inlet)</i>		
Air velocity (m/s)	2.200	0.160
NH ₃ (ppm)	0	0
Turbulence intensity (I)	0.0100	0.0100
Turbulence length scale (L) (m)	0.0142	0.0142
<i>Inlet 2 (compost bed)</i>		
Air velocity (m/s)	0.002	0.002
NH ₃ (ppm) ¹	25	42
NH ₃ (ppm) ²	17	25
Turbulence intensity (I)	0.0100	0.0100
Turbulence length scale (L) (m)	0.4400	0.4400

¹- values measured when hogs were present used for building modeling

²- values measured when hogs were absent used for model validation

To determine ammonia concentration within the building, Dräger (SKC Inc., 2.5-1500 ppm) and GASTEC (SKC Inc., 1-10 ppm, 2-1000 ppm) diffusion tubes that measure the time averaged ammonia concentration for a period of 4 hours were used. To estimate the ammonia concentration in the porous media layer, the average ammonia concentration just above the manure storage area was measured and it was assumed that the gas concentration leaving the porous media layer equals that in the bed. This value was used as the boundary condition at the inlet 2 (table 1) (Figure 5) (Bird et al., 1960).



Assumption: $C_{leaving} = C_p$

Figure 5. Assumption used at inlet 2 to simulate airflow through solid manure bed.

The validation experiments were performed three days after hogs were moved out of the building. Since no fresh urine and feces was deposited in the manure storage area, the surface of the manure/bedding may have been somewhat drier than usual. The average ammonia concentration at inlet 2 was lower than that measured while the hogs were present upstairs. Therefore, the boundary conditions in the model were adjusted during validation to account for this difference (Table 1).

Ammonia diffusion tubes were suspended at two elevations; 1.2 m (4 feet) above the slatted floor in the pig area, and 1.8 m (6 feet) above the slatted floor in the pig area. In total, 8 positions with two elevations were sampled to determine ammonia concentrations at specific spatial locations within the building to compare to model predicted values at the same locations (Figure 2, 6). There were totally two measurements; one in the morning and the other in the afternoon. Each measurement was repeated at least twice.

The agreement between the predicted and measured values was evaluated by calculating the normalized mean square error (NMSE) (ASTM, 2002):

$$NMSAE = \frac{\overline{(C_p - C_o)^2}}{(C_{pm} \cdot C_{om})} \quad (14)$$

$$\text{Where, } \overline{(C_p - C_o)^2} = \frac{\sum (C_{pi} - C_{oi})^2}{n} \quad (15)$$

C_{pi} = (normalized) predicted values

C_{oi} = (normalized) measured values

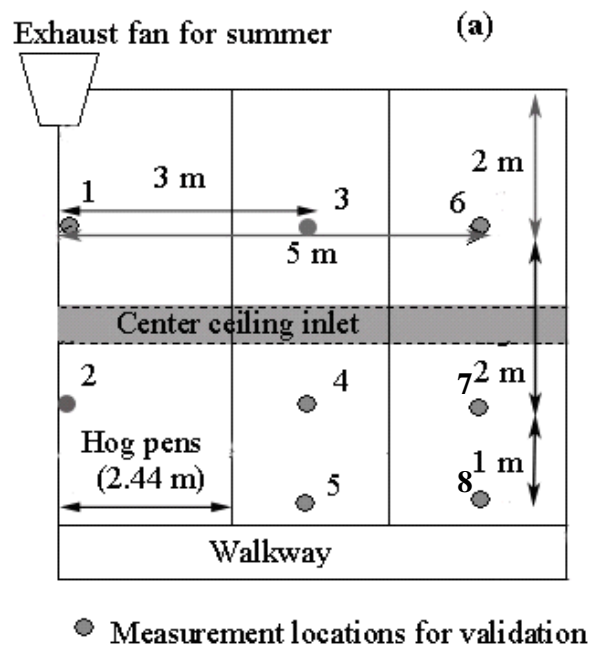
C_{pm} = mean of (normalized) predicted values

C_{om} = mean of (normalized) measured values

n = number of measurements.

When there is a perfect agreement for all pairs of C_p and C_o , the NMSE equals 0. Higher values indicate larger discrepancies in the predicted and measured values. Considering the potential consequences of measurement uncertainties, the calculated NMSE values less than 0.25 are taken as indicators of acceptable model performance in the evaluation of air quality models, (ASTM, 2002).

A non-parametric test, Wilcoxon signed rank test, was also used to compare the measurements with model predicted values at each location (Coffey et al., 2003; Hollander and Wolfe, 1973). This test did not require the assumption that the population was normally distributed. The null hypothesis (h_0) was that the median of the measurements was equal to the model predicted value.



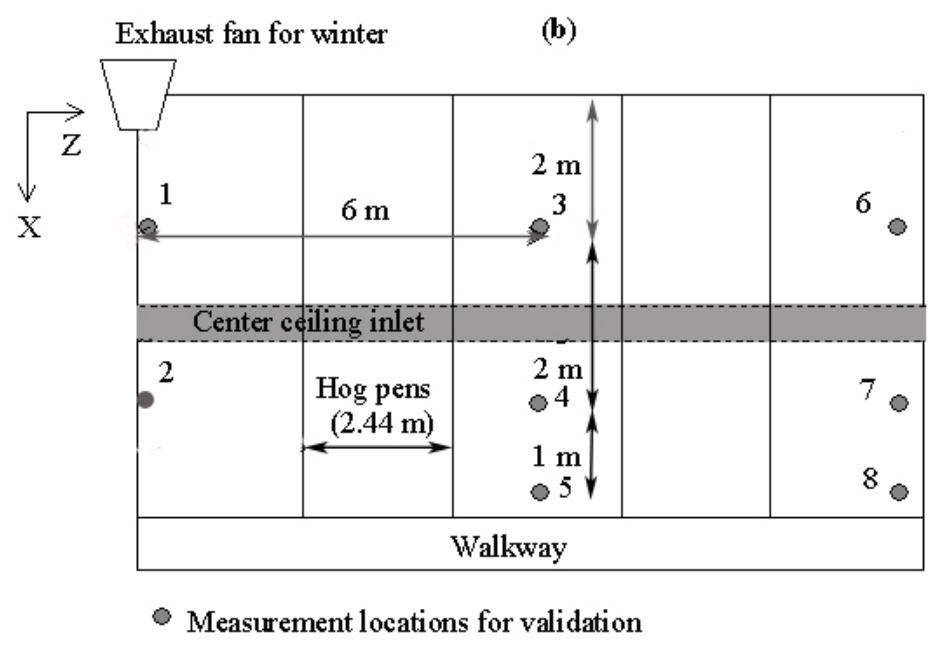


Figure 6. Ammonia measurement locations viewed in a horizontal plane (a) for summer conditions and (b) for winter conditions. Concentrations were measured at heights 1.2 m (4 feet) and 1.8 m (6 feet) above the floor.

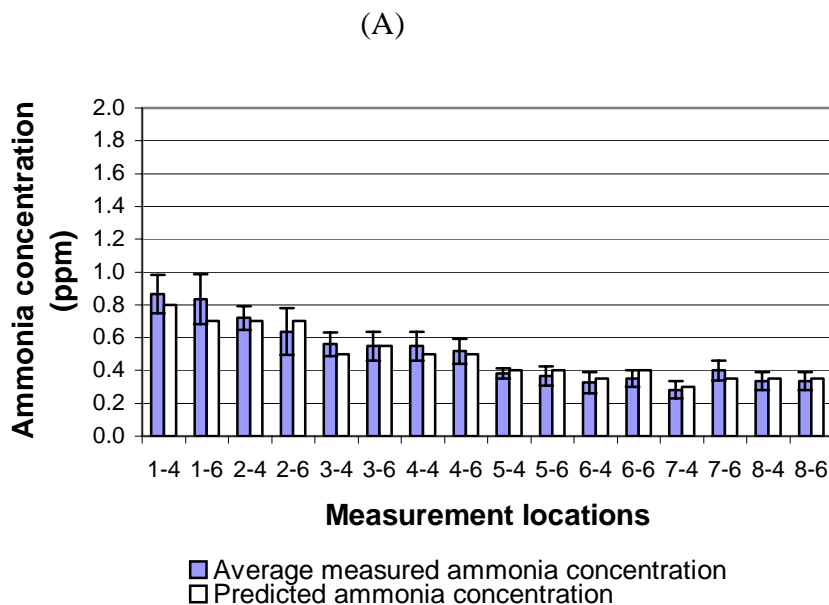
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RESULTS AND DISCUSSION

CFD Model Validation

The CFD models were used to predict ammonia concentrations and air velocities throughout the pig space and the lower story of the HRHB. A comparison of predicted and measured ammonia concentrations at 8 different positions (two elevations) showed that the predicted ammonia concentrations from the CFD model were very close to the averaged ammonia measurements at specific locations in both summer and winter (Figure 11). NMSE values at all 16 sample position were less than 0.25. The average NMSE was 0.025 ± 0.012 for summer conditions and 0.118 ± 0.076 for winter conditions. The results of non-parametric Wilcoxon signed rank test, also showed there was no significant evidence to reject the null hypothesis (data not shown). That is, at each location, the measurements were not significantly different from the model predicted values.

Both the CFD model and ammonia measurements showed that ammonia was not evenly distributed in the pig area in winter. On a horizontal plane, the farther the location was from the exhaust fan, the higher the ammonia concentration was likely to be. On the other hand, the ammonia in the pig area was shown to be relatively evenly distributed in summer. The range of ammonia concentrations were from 0.3 to 1 ppm.



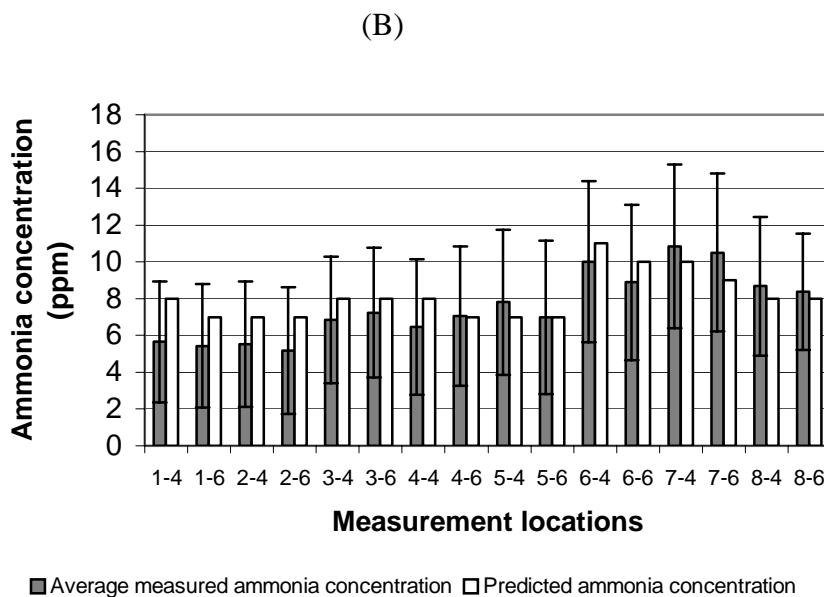


Figure 11. Comparison of average ammonia concentrations ($n = 2$ or 3) and predictions from the CFD models at 8 positions of two elevations within the building (see Figure 6) in summer (A) and in winter (B). Error bars are standard deviations. Measurement location 1-4 represents the point at the position 1 (Figure 6) at an elevation of 1.2 m (4 feet) above the slatted floor.

Airflow Patterns

The CFD models provided a visualization of airflow velocities, pressures and turbulences across the whole building. The airflow pattern was visualized by calculating pathlines, the trace of air particle movement. The simulated airflow pathlines in the building during summer showed that the main airflow pattern was outward from the ceiling inlets and downward within the pig space (Figure 7). Little gas flowed back to the upper story and the air moved in a spiral pattern toward the exhaust fan. In the lower story, the pattern was upward from the drying bed and toward the exhaust fan. No air from Inlet 2 entered the upper story (Figure 7B).

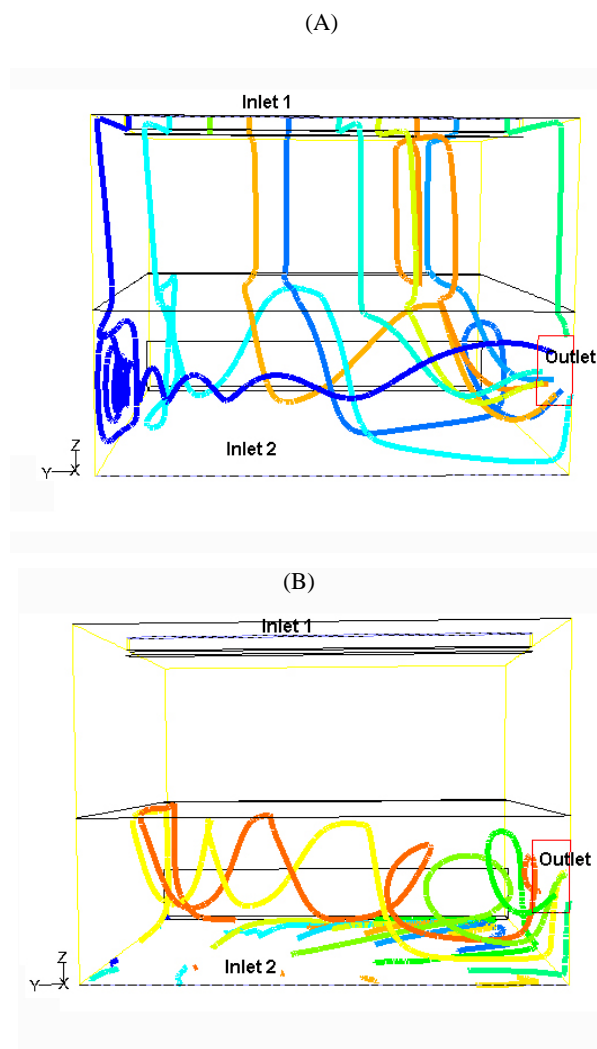


Figure 7. The simulated airflow pathline for summer condition in a HRHB A) Inlet 1 airflow. B) Inlet 2 airflow. Different color represents different air particles.

In winter, airflows were somewhat different than in summer due to lower ventilation rates. The model simulated airflow pathlines showed that two flow patterns existed in the HRHB at the same time (Figure 8). The simulated domain was divided into two parts to illustrate the phenomenon; one far away from the exhaust fan (Section A, Figure 8) and the other close to the exhaust fan (Section B, Figure 8). In section A, the airflow pattern was different in summer and winter. In summer, air entered from the ceiling inlet and flowed outward and downward (Figure 8A). A large vortex was formed across the slatted floor. Some air was predicted to recycle to the upper story (Figure 8A). In winter, air moved more slowly toward the exhaust fan. In the lower story of the building, some of the air that passed through the manure mixture went upward into the hog area, potentially carrying ammonia with it into the pig space. In section B, the airflow pattern in winter was similar to that in summer. Air entered the ceiling inlets, flowed downward through the pig space and toward the exhaust fan (Figs. 8A). Little gas flowed back to the upper story. In the lower story, air flowed upward through drying bed and toward the exhaust. Very

little air from Inlet 2 entered the upper story (Figure 7B). Most of the air coming from section A flowed toward the exhaust in a spiral pattern.

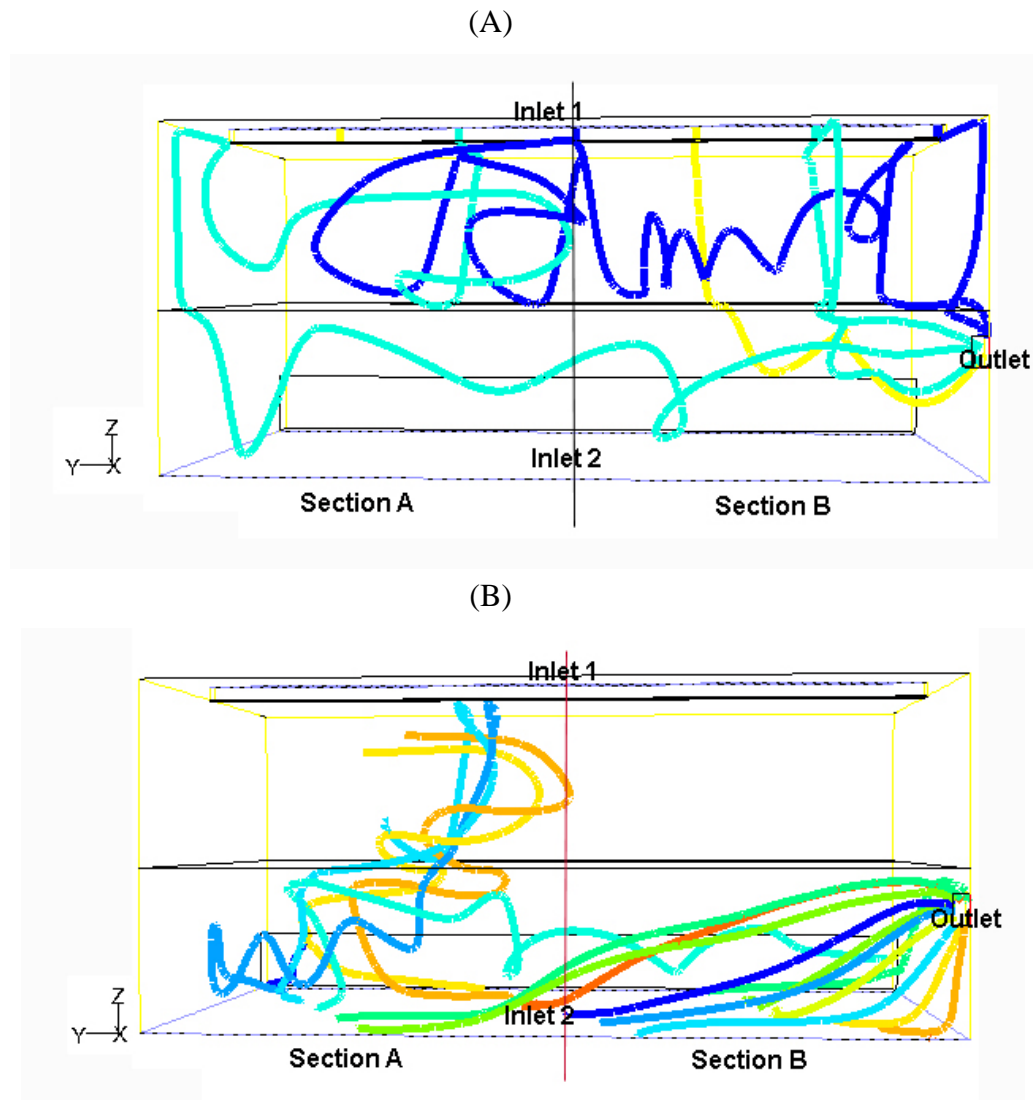


Figure 8. The simulated airflow pathlines for winter conditions in a HRHB. A) Inlet 1 and B) Inlet 2. The simulated space is divided into two parts, sections A and B, for the convenience of description. Different color represents different air particles.

Ammonia Concentrations in Summer and Winter conditions

In summer, the maximum ammonia concentrations on the slatted floor in the pig space were predicted to be below 5 ppm (Figure 9). Ammonia was predicted to be evenly distributed across the pig space (difference less than 1.5 ppm); some locations close to the fan and center of the pen

had higher ammonia concentrations (Figure 9). The model showed the ammonia concentration was from 0.2 to 1.3 ppm at the height of 0.6 m (2 feet) and 1.8 m (6 feet) in the pig area, which was consistent with early measurements (Keener *et al.*, 2001; Stowell *et al.*, 1999).

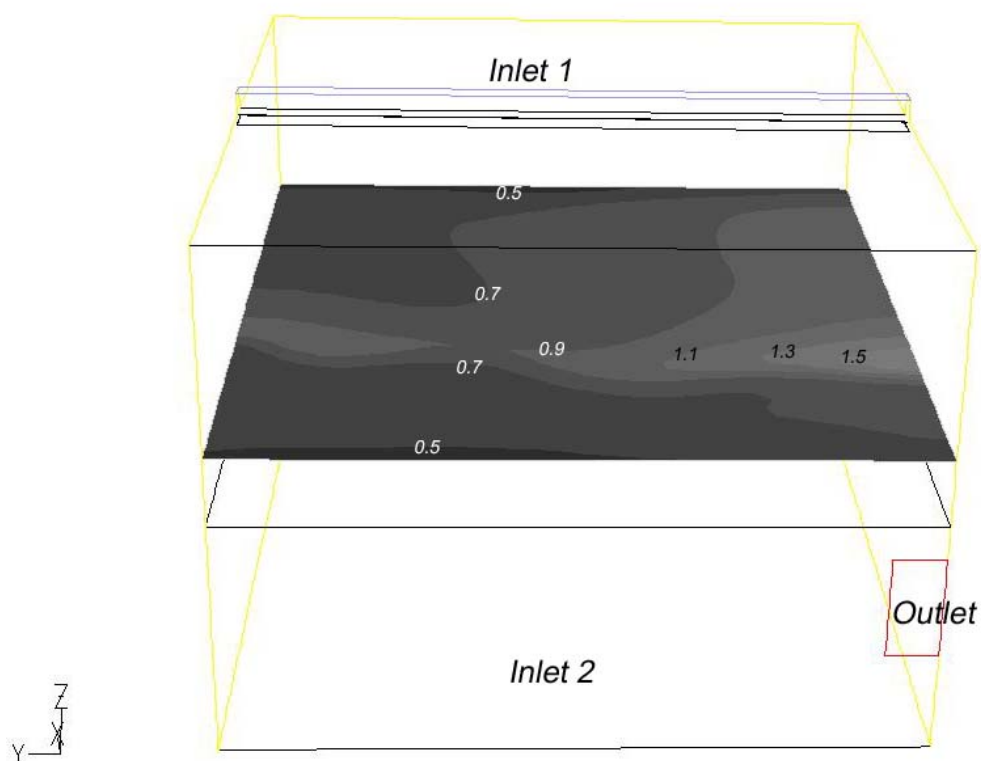


Figure 9. Concentration contour of ammonia for summer condition in a HRHB. The plane about 0.6 m (2 feet) above the slatted floor in the building is selected to show the ammonia distribution throughout the airspace closest to the pigs.

In winter, the maximum ammonia concentration on the second floor in the pig space was predicted to be 29 ppm (Figure 10). Near the walkway the ammonia concentration was around 18 ppm (1 meter high from the walkway surface), which was higher than the average level of 10 ppm in winter, but lower than the highest level of 19 ppm measured by Stowell *et al.* (1999). The highest ammonia concentration was found to occur in the center of the pens. The pens that were far away from the exhaust fan exhibited higher ammonia concentrations. At a height of 0.6 m (2 feet) in the pig area, the ammonia concentrations were from 18 to 29 ppm (Fig. 10).

The ammonia levels higher than 25 ppm represent a risk to the health and well-being of humans and animals. Concentrations greater than 25 ppm exceed threshold limit values (TLVs), over which hog's somatic growth is depressed (Gustin *et al.*, 1994). They also exceeded the ACGIH TWA limit of 25 ppm (ACGIH, 1984). However, these concentrations were only observed in certain parts of the confinement space, primarily in the center of the pens and away from the exhaust fan, and only during periods of minimum ventilation. But if the synergistic

effects of mixtures of dust and gases are considered (Donham, 1993 & 1999; Donham et al., 1989 & 1986), then the ammonia levels in the HRHB, which were always greater than 7 ppm in winter could have an adverse health impact on animals and on workers who do not wear suitable protective gear. Swine confinement buildings frequently experience levels of ammonia well in excess of recommended limits (Buitter and Hoff, 1998). In this regard, the concentrations of ammonia predicted in the HRHB were no greater than the levels observed in conventional deep pit buildings by other investigators (Donham et al., 1986, Donham et al., 1989; Buitter and Hoff, 1998).

An important output of this study was the visualization of air flow patterns and ammonia distribution throughout the building in winter. The air used to dry manure bedding brought pit gases including ammonia from the manure area to the animal area. In order to control ammonia concentrations in the pig area, the aeration strategies of drying manure bedding could be improved to reduce the updraft of air or the ventilation fans could be redistributed or increased to achieve better ammonia distributions (e.g. no ammonia level greater than 25 ppm).

Compared to the two-dimensional CFD model of a HRHB developed by Sun et al. (2002), this model showed clearly the effect of the location of exhaust fans on ammonia concentrations and airflow in the hog area. In winter, ammonia distribution in the pig space was predicted to be strongly related to the horizontal distance from the fan outlet. Furthermore, the 3-D airflow simulations showed that the airflow might have completely different patterns in sections at different distances from the fan outlet. These findings demonstrate the superiority of the 3-D model to the 2-D model.

The results of this study demonstrate the application of a CFD model of an innovative animal housing facility that can be used by designers to optimize air quality in the pig space (for example by analyzing the effects of changing the placement of exhaust fans). This model is also a helpful preliminary step towards the development of even more realistic but challenging non-isothermal CFD models, which account for factors such as animal heat generation and indoor and outdoor temperatures.

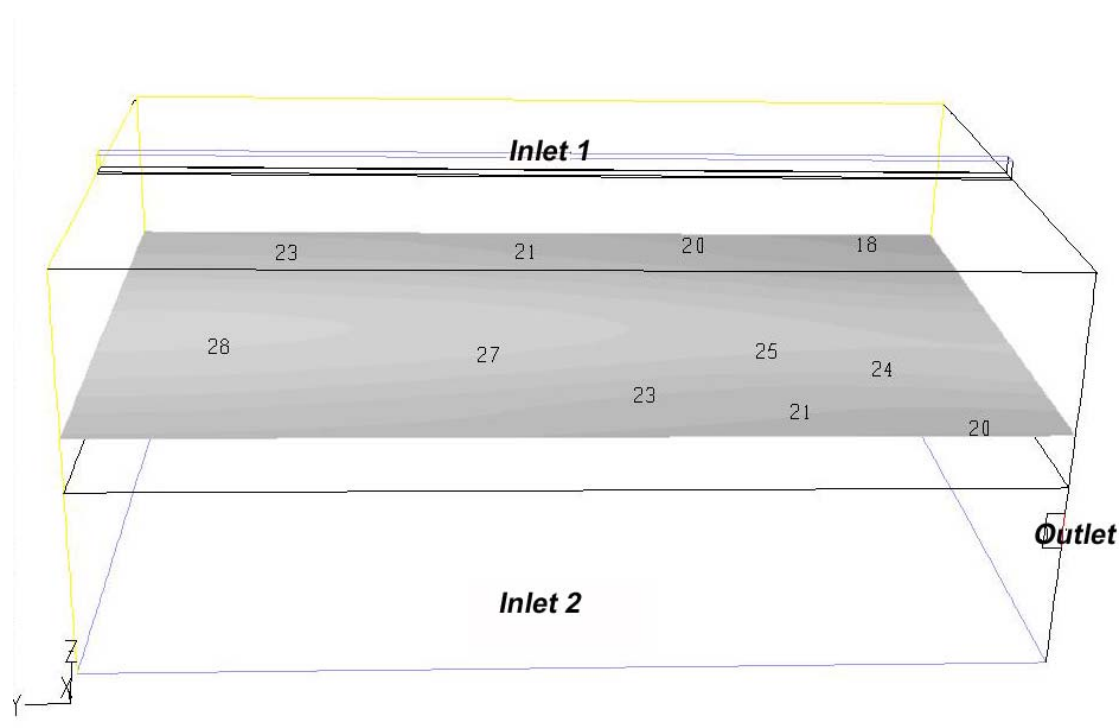


Figure 10. Concentration (ppm) contour of ammonia for winter condition in an empty HRHB. The plane at 0.6 m (2 feet) above the slatted floor in the building is selected to show the ammonia distribution throughout the airspace closest to the pigs.

CONCLUSION

- 1) The close agreement between predicted and measured values of ammonia concentration indicates that these CFD models can effectively evaluate air quality and ventilation system performance across the entire 3-D space of a HRHB and potentially other animal confinement buildings.
- 2) The HRHB CFD models provided detailed information about the time-averaged airflows and ammonia concentrations throughout the entire space of a HRHB that would not be possible using direct measurement.
- 3) The models predicted that the ventilation system of the HRHB kept ammonia concentrations well below levels considered to adversely affect animal health in summer conditions.
- 4) The models predicted that in winter low ventilation conditions, some ammonia from the lower story of the HRHB flowed into the pig space and affected the ammonia distribution in the upper story where maximum concentrations of 29 ppm would occur. This ammonia concentration is similar to the range observed in conventional deep pit buildings and is in excess of recommended limits of 25 ppm.

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