THEORETICAL AND EXPERIMENTAL STUDY OF
A HIGH RISE™ HOG BUILDING FOR IMPROVED UTILIZATION AND
ENVIRONMENTAL QUALITY PROTECTION

DISSERTATION

Presented in Partial Fulfillment of the Requirement for
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Ammonia and liquid waste problems are a great concern for animal producers because of their environmental impacts and effects on human and animal health. A novel swine production system, the High-Rise™ Hog Building (HRHB), has been developed to minimize liquid waste, reduce nutrient losses and control ammonia volatilization. A theoretical and experimental study was done to evaluate nutrient losses and ammonia levels in a HRHB and associate manure management system.

Two groups of hogs, 998 head in summer and 1047 head in winter were studied. Animals grew well with an average weight gain rate of 0.86 kg/pig/day (1.89 lb/pig/day). The feed was consumed at a rate of 2.4 kg/pig/day (5.3 lb/pig/day). The average conversion ratio of feed was about 2.83. At the start of the experiment, sawdust bedding was added at a rate of 45 kg/pig to absorb the moisture from the manure in the lower story. During growth, manure accumulated at an average rate of 0.63 kg/head/day.

The average nitrogen, phosphorous and potassium losses due to volatilization (N) and liquid drainage (N, P, K) from the HRH building in both summer and winter periods were 3.86 kg/head, 0.25 kg/head and 0.76 kg/head, representing 52, 21 and 47% of the initial amount respectively. Beside these losses, about 17% nitrogen, 3% phosphorus, and
4% potassium from the initial manure/amendment mixture was lost during a 100 days composting process.

Ammonia concentrations in the pig space were measured less than 2.5 ppm in summer and as high as 30 ppm in winter. The average ammonia concentration in winter was 16 ± 6.32 ppm. The highest ammonia concentration was found on Dec 4th when the outdoor temperature was below -4°C (25 F) A one-way ANOVA model and two linear regression models were developed that showed lower outdoor temperature and higher indoor/outdoor temperature difference could lead to higher ammonia concentrations in pig space in winter. The $p$-values were calculated less than 0.001.

Computational Fluid Dynamics (CFD) models were developed and validated to investigate airflow pattern and ammonia distribution in HRHB. In winter, the CFD models predicted that some air blown through the manure bed could flow up into the pig space, which could lead to high ammonia concentrations in the upper level of the building. To reduce ammonia concentration in the pig space, 3-D non-isothermal CFD models were used to optimize the ventilation system of the HRHB. The aeration used to dry manure bedding was predicted as a significant factor to cause high ammonia concentration in the pig space. Ceiling inlet size was predicted to keep small in winter to achieve an even distributed temperature profile across pig space. Furthermore, using more small exhaust fans was predicted unnecessary to reduce the ammonia gradient in animal space under a same low air change rate. A comparative assessment of HRHB system versus other alternative hog production systems will be done in the future.
Dedicated to

My parents, my mother-in-law, my wife and daughter,
my sister and her family
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CHAPTER 1

INTRODUCTION

Concern about the potential for animal waste pollution has emerged as one of the most critical environmental issues confronting swine producers in the United States. Based on a survey of America Society of Agriculture Engineers (ASAE) and United State Department of Agriculture (USDA), animals and their waste have been concentrated in fewer farms during last decades. In 1987, 157,000 swine production facilities annually produced approximately 103,000,000 hogs and more than 118,520,000 tons of manure in the United States (ASAE, 1988; Harkin, 1997). Ten years later, swine farms decreased to 102,106, but the number of total hogs increased to 142,611,882. More than 150,000,000 tons of manure were produced and treated in 1997 (USDA, 1997). Excessive manure loading rates in swine production areas lead to a remarkable accumulation of nitrates and phosphorus in surface and ground waters; massive ammonia emissions lead to significant nitrogen deposition; and odors lead to enormous complaints from neighbors and social communities. These problems have become constraints to the profitability and growth of the hog production industry (Boersma and Murarka, 1995; Sutton and Power, 1996).
Currently, most of swine production facilities typically manage manure and wastewater as a liquid, which has low nutrient density and requires high transportation costs. Manure storage and/or treatment systems such as deep pit and lagoon become significant sources to produce odors. Furthermore, these systems have high potential to pollute surface and ground waters, especially when lagoon failure and/or serious leaching occur (Boersma and Murarka, 1995; Menke, 2000). In order to satisfy growing public concern about environmental protection, swine producers have been encouraged to seek new swine housing and manure management systems that can minimize or eliminate the liquid stream, facilitate solid utilization alternatives, control ammonia volatilization and odor, as well as reduce nutrient losses to the environment (Humenik et al. 2002; Williams 2002).

Solid manure handling offers a possible solution to many of the problems associated with liquid systems. A new concept for swine production known as the High-Rise™ Hog Building (HRHB) was developed by industry partnering with The Ohio State University (Figure 1.1) (Keener et al., 1999; Mescher et al., 1999). This system has a two-story construction. Hogs are grown in the second story on a slatted floor and the first story consists of an in situ system for manure management. Unlike conventional swine facilities, which typically have a pit constructed in the ground to store liquid manure, the lower story of the High-Rise™ Hog facility has a floor at or above ground level for manure storage. Wood shavings, sawdust, ground pallets, straw, and/or cornstalks are used in this floor to absorb liquids and provide a porous bed upon which the manure falls. Air is forced up through this porous bed from an in-floor aeration system to dry and
Figure 1.1: High-Rise Hog building: A) photograph of a facility in Darke County Ohio; B) cross-section of the facility (Stowell et al., 1999)
partially compost the manure. A solid, partially stabilized product is removed after 4 or 8 months (production cycle ~ 4 months). This solid partially composted material has less risk of polluting surface and ground water and is suitable for composting in windrows.

All exhaust fans are located in the lower story in the HRHB. Fresh air is drawn through a baffled ceiling inlet into the pig space and down through the slatted floor into the lower story where it is exhausted. This solid handling system can reduce volatile organic odors commonly associated with hogs, as well as the amount of manure that must be ultimately managed. It may provide a new solution to manure management that is socially acceptable, environmentally friendly and economically feasible (Mescher et al., 1999; Keener et al., 1999; Stowell et al., 1999, 2000a and 2000b).

Goals of HRHB are drying and partial composting of the manure to eliminate liquid treatment system costs, improve solid utilization, control ammonia volatilization, reduce odors, optimize hog performance, and decrease negative impact on the environment. However, to completely and successfully meet these goals is not easy. A comprehensive theoretical and experimental study of the HRH system can help designers and hog producers to better understand the system and make a full evaluation of its performance as compared to conventional systems and other alternative hog production systems. The outcomes of this study will enable designers as well as owners to improve the design and optimize management strategies for HRHB, which will help maximize economic return and satisfy increased public concern about environmental impacts of swine production facilities.
Various studies have been done to investigate the performance of HRHB. Hogs were grown from 20 kg to 120 kg. The manure in a HRHB had low moisture content (63%). Hydrogen sulfide was not detectable at levels above 0.2 ppm. The average CO₂ concentrations were below 1300 ppm. Ammonia levels were kept below 20 ppm in the pig space (Stowell et al., 1999; Keener et al., 2001). Nitrogen losses from HRHB and composting process were estimated as 70 to 73% of the excreted N (Michel et al 2001). However, none have provided a full evaluation of nutrient flow through the HRH system and a comprehensive investigation of air quality in the building.

This dissertation performs a theoretical and experimental study of the HRH system, which includes two sections, a nutrient mass balance around a commercial HRHB and air quality simulation study.

Mass balances on feed, animal weights, water use, total Nitrogen (N), Phosphorous (P), and Potassium (K) in a HRHB system are used to determine the ultimate fate of each component through the system, and to account for the nutrient losses from the building and their impacts on the environment. The mass balance outputs allow a comparative assessment of the nutrient loss from the HRHB with other alternative livestock product systems. Previous studies found the nitrogen loss from the HRHB were comparable to those from conventional swine buildings (Keener et al., 2001; Michel et al 2001). No studies have been done to investigate phosphorous and potassium losses from HRHB.

Air quality in a confinement animal building has been of high concern (Cormier et al., 1998; Donham et al., 1986; Donham et al., 1999; Zejda et al. 1993). As one of the
newest confinement livestock facility designs, the High-Rise™ Hog Building (HRHB) is also facing the same requirement of maintaining optimum air quality in the building. In this study, Computational Fluid Dynamics (CFD) models were developed to predict airflow characteristics and ammonia distributions in both empty and occupied HRHBs. Ammonia concentrations throughout the pig area were also measured to provide an ammonia profile in the animal space and to validate the CFD model. Ammonia emission from HRHB was monitored intermittently throughout an entire hog growing cycle, which is an important addition to the database of ammonia emission from animal industries (Arogo et al., 2001; Phillips et al., 1999, 2000 & 2001; Ni et al., 1999).

Animal performance and operational cost are two important evaluation criteria for swine housing systems. Animal growth data and operational fees were collected based on financial reports from the cooperative hog producers. These will be used for a comparative assessment of HRHB with other alternative hog production systems.

The main focus of this research was to develop a uniform method and perform a comprehensive theoretical and experimental study of HRHB for improved animal production and environmental quality protection. In this study, nutrient losses from the building, air quality in pig space, animal performance and operational costs were investigated.

Chapter 1 provides the impetus of this dissertation. Significance and concerns of performing theoretical and experimental study for the HRHB are discussed. Chapter 2 presents the specific objectives of the study. Chapter 3 reviews the previous and current state of the study of mass balance on animal production, air qualities in animal building,
and CFD simulations of ventilation in animal facilities. Chapter 4 provides the methods and materials used in this study. The governing equations and boundary conditions of CFD models have been defined and listed. Chapter 5 presents the results and discusses the data obtained. Chapter 6 summarizes the achievement and discusses the further steps of this study. Appendixes explain and test several procedures that are used to achieve parameters used in this study.
CHAPTER 2

OBJECTIVES

The overall goal of this study was to develop a uniform method and fully evaluate the performance of HRHB for improved animal production and environmental quality protection. The outcomes will allow a comparative assessment of the HRHB system versus other alternative hog production systems.

The overall objective was achieved through the following specific objectives:

- to evaluate the nutrient management system of HRHB by using mass balance analysis, determine the nutrient losses from the building;
- to use CFD modeling for the study of airflow and ammonia distribution in the pig space, optimize ventilation system to achieve better air quality;
- to generate the ammonia profile in the animal space by measuring ammonia concentration and validate the CFD models. Estimate ammonia emission from the building by using modeling and ammonia measurement;
- To investigate animal performance and prepare for the comparative assessment of HRH system versus other alternative hog production systems.
CHAPTER 3

LITERATURE REVIEW

During the last decade, swine facilities and their associated manure management systems have been under increasing environmental scrutiny from regulators as well as the public (Humenik et al. 2002). Hog farms have been blamed for being a significant source of phosphorus and ammonia that have severely degraded environmentally sensitive areas (Boersma and Murarka, 1995; Sutton and Power, 1996; Keener et al. 2001). Swine waste lagoon failures cause serious pollution of ground and surface waters, especially lakes or fishery ponds. Widespread odor complaints also originate from swine producers. To address these issues, increased attention from hog producers has been directed to the need for new swine housing and manure management systems that can minimize or eliminate the liquid stream, facilitate solid utilization alternatives, control ammonia volatilization and odor, as well as reduce nutrient losses to the environment (Garrison et al., 2001; Humenik et al. 2002). However, these multiple requirements have made the design of new facilities and development of appropriate compliance strategies more difficult, as systems that offer benefits in one area may disadvantage another.
Currently, many innovative swine housing/manure collection systems are being evaluated as part of the Smithfield agreement (Humenik et al. 2002). Unfortunately most of these systems still rely on liquid based manure handling. A recent project specifically designed to evaluate four novel solid based manure handling systems has been funded by the six state consortium for animal waste management and the EPA Animal and Poultry Waste Management Center. These four systems are a scraper system for fecal/urine isolation developed by Michigan State University, a deep-bedded hoop structure by Iowa State University, a belt system by North Carolina State University, and the High-Rise Hog system (HRH) by The Ohio State University (Humenik et al. 2002). A similarity of these systems is that each provides a solid waste stream that facilitates further treatment by drying, composting, or conversion to energy, and eventually to value-added byproducts. These technologies may allow hog producers to reduce or eliminate liquid systems, minimize odors and ammonia evaporation and decrease nutrient losses to the environment. Each of these systems has its own advantages based on facility construction cost, operational savings, and by-product generation. In order to make a comparative evaluation of these four systems, Humenik et al. (2002) suggested developing a uniform assessment and quantifying characters of each system, which included several techniques such as mass balance study, air quality evaluation, animal performance and economic analysis. This approach was believed to be an important tool for documenting the advantages of these systems.

Developing a uniform method of evaluation and performing a theoretical and experimental study of HRHB was a main objective of this study. The following sections
review the literatures on (1) mass balance studies of livestock production/manure management systems; (2) Air quality in animal production facilities; (3) Modeling airflow patterns in animal facilities.

3.1 Mass Balance and Nutrient Losses from the System

Mass balance analysis has been widely used to study nutrient losses from livestock facilities and manure management systems (Keener et al., 2001; Michel et al., 2001; Garrison et al., 2001; Tyrrell, 2001; Sommer & Dahl, 1999; Pedersen et al., 1998; Tiquia et al., 2000; Gustafsson, 1999). This approach can provide important insights on all types of animal production systems, especially when evaluating multiple design objectives such as reducing odors and all hazardous gas emissions, decreasing operational costs and improving the production rate. By quantifying the different pathways of inputs and outputs from the system, the ultimate fate of each nutrient can be clarified and the relative significance of different types of nutrient losses can be more readily compared between systems.

Tyrrell (2001) summarized the application of mass balance analysis in animal agriculture. He wrote, “To fully evaluate a nutrient management system for a livestock or poultry production facility, one must step back to basic physical laws of matter and apply the principle of mass balance to understand the ultimate fate of each nutrient as it flows through the production system”. The principle of mass balance analysis states that nutrients in elemental form are neither created nor destroyed in the system. However, their chemical form may be altered. Nutrients entering the system should be accounted
for either as components of products leaving the system or as products accumulating within the system. Mass balance accounting becomes complicated for the study of animal facilities since elements can be components of different products, e.g., gases, solids and microorganisms. In some cases (for example ammonia) this necessitates quantification of emissions from livestock facilities by difference of the unaccounted for mass of N in the system (Tyrrell, 2001).

As an example, Keener et al. (2001) evaluated ammonia emissions for a HRHB using this nitrogen balance method with the formula: Ammonia nitrogen = Feed nitrogen – Carcass nitrogen – Manure nitrogen. The estimated weight of the bedding and the generated manure/bedding mixture was used in the calculation. The results showed that about 6.46 kg ammonia/pig was emitted every year which is close to the cited value of 6.98 kg ammonia/pig/year for conventional finishing swine system (Battye et al., 1994). Keener et al. also found that extensive data collection of weights and chemical properties of all materials into and out of the HRHB would be needed to document expected emissions and provide guidelines on management options to minimize NH₃ emissions.

In another study, Michel et al. (2001) estimated the nitrogen and water losses from a commercial HRHB using a similar mass balance approach. Totally, two trials (Run 1 and 2) were conducted in a commercial HRHB. Wood shavings were used as bedding at depths of 61 cm (Run 1) and 30 cm (Run 2). In Run 1, two cycles of hogs were finished while in Run 2 only one cycle of hogs was finished. Results of mass balance calculations based on feed intake, and protein level in the finished hogs and N content of the manure/bedding mix upon removal from the house showed that from 70 to
73% of the excreted N, and 79% of the excreted water had been lost during manure accumulation in the house. These losses were probably due to ammonia volatilization and to water evaporation and removal by ventilation.

Both Keener et al. and Michel et al. did mass balance analyses for the study of nitrogen loss in the HRHB. However, some estimates of weights and chemical properties of materials had to be used. The results could be improved by collecting extensive data for all materials into and out of the HRHB. Furthermore, both of the studies focused on nitrogen loss. No research had been done on the fate of phosphorus and potassium in the HRHB. These elements might be significant contributors to surface and groundwater pollution through leaching and runoff during animal production and composting. Therefore, additional research was needed to fully evaluate the nutrient loss from the HRHB and the associated composting process.

Garrison et al. (2001) examined the nutrient losses for bedded swine facilities and associated composting piles over two years. Nutrient mass balances were completed on three groups of pigs in naturally ventilated hoop structures, along with the corresponding three composting trials at the outdoor windrow composting site. A considerable amount of nitrogen was lost from the hoop structure. These losses were about 54±5% of the excreted manure nitrogen (3.9 kg/pig) or 45±11% of the total nitrogen input to the hoops. The phosphorus losses within the hoops were negligible. But at the composting site, both N and P losses were significant (19±10% and 21±21% of the excreted manure respectively). Only 1.9±0.4 kg N/pig and 1.0±0.3 kg P/pig remained in the final compost product after losses in both the hoop and the composting process. Most N losses appeared
to be in the gaseous forms, e.g. Dinitrogen, Ammonia and N₂O. 10% or less of N losses
from the hoops accumulated in the topsoil (first year result). Leaching of N from the
composting pile into the soil was also observed.

In a separate study, Tiquia et al. (2000) conducted a mass balances analysis of the
bedded pack in a hoop structure and during the subsequent composting process with
initial bedding C:N ratios from 9:1 to 21:1. The results of N input and output calculation
for the hoop revealed that 35 to 45% of the initial N in the facility was lost during the 5-
month feeding period. The composting process, regardless of initial bedding C:N ratios
used, significantly reduced the nutrient content of hoop manure. Less than half of the
total N content of the hoop manure remained in the final compost product. It appeared
that the lower initial C:N ratio (between 9:1 and 12:1) had a major effect on N loss in the
composting process. High P, K and N losses (about 23-39%, 20-52% and 32-53%
respectively) were also found during composting, which could be due to runoff and
leaching from the hog manure.

Thelosen et al. (1993) conducted a nitrogen mass balance around two deep litter
systems (Ecopor and Envistim (Finnfeeds)) for finishing pigs. They found that
approximately 3 kg nitrogen/pig was lost in both deep litter systems during each
production cycle during which pigs grew from 25 kg to 105 kg. The nitrogen lost as
ammonia and N₂O per pig place was 0.7 kg and 0.2 kg for the Ecopor deep litter system,
the remaining nitrogen could be released as N₂. Ammonia and N₂O emissions from the
Envistim system were not measured.
Nelson and Mikkelsen (2001) did phosphorous mass balance analyses on a conventional deep pit hog farm. By quantifying the P imports and exports from the system, approximately 7,700 kg P yr\(^{-1}\), equivalent to 55% of total P used accumulated. On the farm, 90% accumulated in the lagoon, a component of liquid manure treatment system. This continuous accumulation of P has great potential to pollute surface and ground water, especially when lagoon failure or leaching occurs.

Mass balance was also used to estimate nitrogen losses caused by denitrification during the composting of deep litter (Sommer and Dahl, 1999). All measurements were made in a dynamic chamber. Gas emissions and leaching of nutrient during composting were determined. Total losses of N, P content and dry matter content were calculated. The ash and P content were assumed to be constant and used for correction of dry matter in the chamber. The results showed that ash content could change during the composting, probably due to the formation of solids of Ca, carbonaceous components and phosphorus. Therefore, P was a more accurate tie component than ash in the calculation of the nutrient losses during composting. Based on their mass balance, N losses during composting due to leaching, ammonia emission and denitrification were 5-19% of the initial N.

However, using P as a tie component is not suitable for composting processes where the leaching and/or runoff of P from composting piles is significant and uncollected. Under these situations, the mass of ash in windrows has been used as a tie component during composting to determine nutrient losses (Garrison, et al. 2001).

Keener et al. (2001a) did a nutrient balance for a 1.6 Million caged layer facility using a controlled volume approach based on N/ash ratios. Two methods were used for
calculation of N balance, one using airflow based on the fan rating and incorporating ammonia levels within the exhaust plume; the other based on monitoring solids leaving the operation and levels of ash and nitrogen in each stream. The ash content of the bird was assumed to be constant. The ash of the product including manure and egg equaled the ash of the feed. The mass balance was done for two systems, a manure belt/composting system and a deep pit operation. Results showed that the belt/composting systems had a N retention in compost of 0.560 kg/bird/year versus 0.265 kg/bird/year in deep pit manure. This indicated that N emission from the belt/composting system could be less than that found in conventional deep pit system and provided a way for improved conservation of N.

Phillips et al. (1999) reviewed 4 possible approaches for ammonia measurements from livestock buildings and manure storage areas, these being feed/manure nitrogen balance, summation of local ammonia sources, determining ammonia fluxes, and measuring ammonia sources to air by a tracer ratio method. A comparison of the ranking of these methods is shown in Table 3.1. Although the nitrogen balance approach was not valued as the best method for the measurement of ammonia concentration, it was shown to be a useful method, which was suitable for house and storage use, had high meteorological flexibility, and required low running and capital cost.

However, ammonia emission is not the only source that contributes to nitrogen losses from livestock buildings and manure treatment and storage areas. The sources may include NOₓ emissions, drainage of wastewater, leaching to the topsoil, and runoff during composting, which depends on different housing systems, operation strategies, pH, and
bedding materials. The more other sources contribute, the farther the mass balance results deviates from the true ammonia emission value. Determining other sources’ effect as much as possible will lead to more accurate estimates of ammonia emission using mass balance approaches.

In summary,

- Mass balance approaches can be used for evaluation of nutrient losses from HRHB systems.

- N losses from animal facilities appear to be significant. Nitrogenous gas emission is a major contributor for N loss in the facility.

- Both N and P losses from open air composting windrows (without waterproof covers or bases) are significant, which could be due to ammonia emission, runoff or leaching during the composting process. The mass of ash in windrows can be a tie component for mass balance analysis during composting.
### Table 3.1: Ranking of possible approaches for determine ammonia emission rate from animal building (From Phillips et al., 2000)

<table>
<thead>
<tr>
<th>Aspect</th>
<th>I Nitrogen balance</th>
<th>II Ammonia summation</th>
<th>III Ammonia fluxes at a chosen envelope</th>
<th>IV Measuring sources</th>
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<td></td>
<td></td>
<td>IIa Measurement</td>
<td>IIIa Measuring air velocities and ammonia concentrations</td>
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<td></td>
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<td>IIb Modelling</td>
<td>IIIb Measuring air dilution</td>
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<td></td>
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<td></td>
<td>IIIc Modelling air velocities and ammonia concentrations</td>
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<td>IIIId Modelling air dilution</td>
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<td>AMANDA</td>
<td>Wet chemistry</td>
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<td>Quick turn around</td>
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<td>House and store use</td>
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<td>Meteorological flexibility</td>
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<td>Ease of procedure</td>
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<td>Running costs</td>
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<td>Capital costs</td>
<td>5</td>
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<td>Repeatability</td>
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<td>Bias</td>
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<td>Time resolution</td>
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<td>Operator skill</td>
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<td>Range</td>
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<td>Comments</td>
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<td>Problems with imperfect mixing</td>
<td>Not good with complex topography</td>
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<td>Depends on instruments used</td>
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AMANDA, ammonia measurement by annular denuder sampling with on-line analysis.

Table 3.1: Ranking of possible approaches for determine ammonia emission rate from animal building (From Phillips et al., 2000)
3.2 Air Quality and Ammonia Concentration

Among numerous gases generated in animal production and manure treatment and storage units, ammonia has been of high concern because of its significant effect on human health, animal behavior and the environment (Brautbar, 1998; Monteny & Erisman, 1998; Arogo et al., 2001; Peet-Schwering et al., 1999; Groenestein & Faassen, 1996; Andersson, 1998 & 1996; Phillips et al., 1999, 2000 & 2001; Misselbrook et al., 2000; Pain et al., 1998; Ni et al., 1999; Dourmad et al., 1999; Demmers et al., 1999; Aarnink & Elzing, 1998). Ammonia exposure may lead to acute inflammation in the lower respiratory tract (Brautbar, 1998). Ammonia concentrations greater than 25 ppm has been shown to markedly depress hog somatic growth (Gustin et al., 1994). Extremely high levels of ammonia, such as 5000 ppm, can be fatal to humans and animals (Jones et al., 1998; Schiffman et al., 2001; Jacobson et al., 2001; Heber, 1990). Ammonia emission to the environment can cause severe acidification of the soil (Koerkamp et al., 1994; Groenestein & Faassen, 1996). Furthermore, U.S. Environmental Protection Agency (EPA) made some changes in the National Ambient Air Quality Standards of the Clean Air Act that modified particulate matter (PM) standards to reduce mass median diameter from 10 micrometers (PM10) to 2.5 micrometers (PM2.5). Because ammonia in the atmosphere can react with other compounds, primarily SO2 and NOx, to form fine particulate aerosols that contribute to PM2.5 in the ambient air, ammonia from livestock production facilities may soon become a regulated pollutant with the adoption of the PM2.5 standard (Arogo et al., 2001; Tyrrell, 2001). Therefore, the reduction of ammonia
concentrations within and outside of the animal facilities will become a critical issue for animal producers.

Equipped with the forced aeration and exhaust systems, the HRHB is designed to offer low ammonia environment for pigs and their caretakers (Stowell et al., 1999 & 2000; Keener et al., 2000). Since the first HRHB was built in 1997 in Darke County, OH, various studies have been done to investigate air quality within the HRHB. Keener et al. (1999) measured ammonia concentration bimonthly at three locations within the basement aisle (Figure 3.1). Locations were 10 feet from the east and west ends and in the middle of the basement. During the summer when high ventilation rates were used to cool the building, ammonia levels were generally below 40 ppm. However, during the winter when only small exhaust fans were used to maintain room temperatures greater than 17°C, ammonia levels reached 80 ppm. At no times were ammonia levels near the IDLH values of 300 ppm. In addition, ammonia concentrations were always below 20 ppm in human aisle ways in the middle of the basement.

Keener et al. (2001) also evaluated the air quality in a HRHB with continuous or intermittent aeration through manure bedding. Both studies showed that ammonia levels were lower than 22 ppm in the occupied space throughout the test periods, but exceeded the OSHA 8 hour permissible exposure (PEL) limit of 50 ppm in the lower story during the minimum ventilation period in winter. Suitable protective gear was needed for operators entering the lower story. Continuous aeration removed more liquid from the hog manure than intermittent aeration. But the nitrogen levels and C:N ratios were not significantly different between two aeration condition studies.
Figure 3.1: Previous ammonia sampling location at an elevation of 1 meter above the second floor (Stowell et al, 1999)
Stowell et al. (1999) investigated air quality and airflow within a 1000-head High Rise™ swine finishing facility. All measurements in the building were taken at the same three locations as those selected by Keener et al. (Fig. 2). The concentration of ammonia in the pig space was shown to be quite low with a mean of 4.3 ppm and no readings exceeding 20 ppm throughout the year. In the lower story ammonia levels regularly exceeded 20 ppm and one reading exceeded 120 ppm during the minimum ventilation period in winter. The average concentration downstairs was 23.3 ppm. Stowell et al. also measured ammonia concentration at exhaust fans. Apparent variability from one sampling date to the next was found. The overall mean concentration of ammonia in the exhaust air was 18.3 ppm which is about 10-50% lower than that within the lower story. Furthermore, Stowell et al. documented the bulk movement of air based on an observation of smoke movement. Fresh air rapidly mixed with room air once it curved away from the ceiling. In the lower story, a well-defined interface existed as a horizontal plane between air that arose from the aeration manure/bed mix and air that was drawn downward through the slatted floor. The position of this interface was about 0.5-1 m below the slatted floor in winter and a similar distance above manure/bedding in summer. Little upward and downward movements were observed. No air in the lower story was observed to move upward through the slatted flooring. However, smoke tests were not performed throughout the building and were only performed at noon. Therefore, information about airflow patterns in a HRHB was limited.

Stowell et al. (2000) evaluated gaseous emissions from a HRHB by measuring ammonia concentrations in exhaust air from a 960-head HRHB and of air downwind
from the facility. The mean ammonia concentrations in exhaust air from selected fans were 19.9, 15.6 and 18.1 ppm for the northwest, northeast and southeast fan locations, respectively. The overall mean concentration of ammonia for the 16-month study period was 17.9 ppm. There was considerable variation in the ammonia concentrations of exhaust air from the total number of fans that were operating at any given time. The average mean concentration and standard deviation for seven available sampling dates was 16.1±11.6 ppm. The average ammonia concentration within the exhaust air from fans in northwest, northeast, southeast and southwest quadrants were 18.5, 18.4, 13.5 and 12.6 ppm, respectively. Because of the large deviation of measured airflow velocity and ammonia concentration in the exhaust air, projected total ammonia emission rates ranged widely from 4.1 to 59.0 g/min for the whole HRHB.

Both Keener et al. (2000) and Stowell et al. (1999) found that ammonia concentrations in the upper story of the building were below 20 ppm. This level is lower than the threshold limit value (TLVs) of 25 ppm, but over the exposure limit of 7 ppm suggested by Donham and his colleagues considering the synergistic reaction of combined mixtures of dust and gases (Donham, 1993; Donham et al., 1989). Moreover, most of their ammonia measurements were taken at three locations in the aisle way in both upper and lower stories. Thus the overall ammonia distribution in the entire pig space was not determined. Preliminary experiments showed that ammonia concentrations up to 30 ppm were measured across the pig space in winter. These levels would be expected to have adverse effects on animals and workers. Therefore, a deeper understanding of ammonia distribution and airflow patterns in the HRHB could be useful
to help engineers or hog farmers optimize the design and operation parameters, e.g. ventilation rates, fan performance, inlet size and fan numbers, for the improvement of air quality within the building. To generate a 3 dimensional picture of the ammonia distribution and airflow pattern, extensive measurements would be needed at many distributed locations overtime.

Presently, several techniques ranging from acid traps to Open-Path Fourier Transform Infrared (OP-FTIR) are used for measuring ammonia concentrations (Arogo et al., 2000). Most of these measurements are either expensive or limited by their practicability in situ. No standard techniques are well accepted (Phillips, et al. 2001). Furthermore, the determination of airflow patterns at low velocity in a full-scale building is difficult and expensive though there are several anemometry techniques such as hot-wire anemometer (HWA) (Benjamin, et al. 2002; Wang and Ogilvie, 1996), and laser Doppler (LDA) (Tropea, 1995; Adrian, 1996) available. Particle Image Velocimetry (PIV) is a powerful technique for visualization of air movement in the building (Hinsch, 1995; Zhao, 2000). However, its application is currently limited by the equipment cost and operation skill requirements. For animal producers or engineers, using modeling to simulate ammonia distribution and airflow pattern in the building may be a more cost effective and efficient approach to understand air quality and ammonia concentration in animal facilities.
In summary,

- Among numerous gases generated in animal and manure store units, ammonia has been of high concern because of its significant effect on human health, animal behavior and the environment.
- Ammonia concentrations in the HRHB were found to be below 20 ppm at limited locations. A level of 30 ppm was recently measured across the pig space in winter, which could have adverse effects on animals and workers.
- Extensive measurements are needed to obtain 3-D distribution picture of airflow pattern and ammonia distribution in the HRHB. These measurements are either expensive or limited by their practicability in situ. No standard techniques are well accepted.

3.3 CFD Modeling to Determine Ammonia and Air Velocity in Animal Facilities

The Computational Fluid Dynamic method (CFD) has been widely used to study airflow in green houses, animal buildings and human rooms (Short, 1996; Lee & Short, 2000; Fan, 1995; Harral et al., 1997; Quinn and Baker, 1997; Jackson et al., 1999; Ayad, 1999; Gan, 1995; Bjerg et al., 1999; Svidt et al., 1998). Compared with other methods to determine airflow patterns in hog buildings such as tracer gas methods (Mueller, 1996) and anemometry (Benjamin, et al. 2002; Wang and Ogilvie, 1996), CFD simulation provides precise solutions and visualizations of velocity, pressure, temperature, turbulence and gas concentrations throughout the entire building airspace without extensive testing of a full-scale physical model. The results allow engineers and operators...
to develop new compliance strategies for improved air quality in, and from the building (Lee and Short, 2000).

Since HRHB is a newly developed swine building, no CFD studies have been done before. In this section, some previous CFD studies on conventional or other alternative animal facilities are reviewed. Generally, for simplification purpose, empty buildings were studied, in which heat transfer and geometric modeling of animals were neglected. Harral et al. (1997) used PHOENICS, a CFD program, to predict airflow patterns in a mechanically ventilated livestock building without animals. The results showed that use of a standard turbulence model to simulate the turbulence energy generation and dissipation could be used to predict turbulence energy distribution in the room.

However, if simulating airflow in an occupied building, the effect of animals may not be negligible considering heat and momentum transfer. Smith et al. (1999) investigated the effects of animals on commonly measured characteristics of airflow. Air velocities in the occupied zone of an experimental slot-ventilated piggery with near-isothermal, rotary airflow were determined using an ultra-sonic anemometer. The determinations were made at eight points at 20 or 40 cm from the floor. Four situations were considered: when the piggery was empty, when it housed unheated models of pigs, and when it housed pigs either in an active or quiet state. The results indicated that the occupants of livestock housing affect the airflow around them, and had substantial effects on the characteristics of airflow in the buildings.
Zhang et al. (1999) studied the effects of internal occupants and supplement heating on fresh ventilating air distribution in an enclosure using both measurement and CFD modeling. Air motion in a thermal buoyant flow caused by free convection around a livestock body was investigated. A simulated pig, made of a painted metal tube with covered ends and heat elements inside, was used as the heat source in the experiments that was carried in a full-scale room. The results showed that velocity and temperature profiles of the plume generated by the simulated pig could be characterized as Gaussian distribution curves in the central radial plane. The buoyant flow remained laminar for some distance before it became turbulent. The CFD simulation provided similar results to the measurement, indicating it could be a potential method to predict buoyant flow in the building caused by animals.

Bjerg et al. (1999) also used CFD models as a tool to predict airflow in livestock rooms and conducted an evaluation of the model by experiments. They investigated the influence of pen partitions and heated simulated pigs on airflow in a slot ventilated test room. Four guiding plates were mounted beneath the ceiling in the test room to obtain two-dimensional flow in the occupied zone. Both measurements and CFD simulations showed that the introduction of pen partitions and thermal pig simulators reduced the air velocities in the occupied zone of the test room. Detailed geometric modeling of the animals might often be unnecessary for simulation of airflow in livestock rooms. This would especially be the case when the animals were located close to pen partitions or other large obstacles in the occupied zone. Poor ability to predict re-circulating zones
could limit the expected precision of CFD calculations with the standard $k$-$\varepsilon$ turbulence model in livestock rooms where re-circulating zones often occur (Bjerg et al. 1999).

Wu and Gebremedhim (2000) used 3-D body–fitted coordinate system to characterize the cow shape. Qualitative and quantitative analysis based on a 3-D CFD model were performed to determine the effect of cow orientation with respect to direction of air flow on convective heat exchange between the cow and its environment. No significant influence of cow orientation on heat convection was found.

Gebremedhim and Wu (2000) presented a CFD model for the simulation of heat and mass transfer in a wet skin surface and fur layer. The model predicted evaporation and convection heat losses for different levels of wetness, air velocity, ambient temperature, relative humidity and fur properties. Evaporative heat loss was not affected at the ambient temperature because the skin temperature tended to be consistent. However, convective heat losses were highly relative to air temperature. Furthermore, the convective heat losses were not affected by the level of wetness of surface, but were related to air velocity and humidity.

Both Wu (2000) and Gebremedhim (2000) simulated a single animal or a piece of skin surface. No animal activities were involved. However, based on the research discussed above, it may not be necessary to include the detailed geometry, orientation, skin wetness, and movements of a large group of lying or standing animals in the CFD modeling to study the airflow in the building. Relatively simple models of the animals can be used (Svidt et al., 1998).
Since room airflow is rarely laminar especially under high ventilation conditions, several turbulence models have been used in CFD studies, these being standard $\kappa$-$\varepsilon$ model (Launder and Spalding, 1972), Renormalization-group (RNG) $\kappa$-$\varepsilon$ model (Yakhot et al., 1986) and Realizable $\kappa$-$\varepsilon$ model (Shih et al., 1995). The standard $\kappa$-$\varepsilon$ model has often been used in the simulation of airflow in greenhouses and animal facilities (Lee & Short, 2000; Murakami et al., 1989). However, the RNG model may provide more accurate simulation results for low ventilation conditions by using an analytically derived differential formula for effective viscosity, which is useful for low-Reynolds-number effects (Yakhot and Orszag, 1986; FLUENT, 1998). The Realizable $\kappa$-$\varepsilon$ model is a relatively recently developed model. Presently, it is not clear under which conditions the Realizable $\kappa$-$\varepsilon$ model consistently outperforms the RNG model.

In summary,

- CFD modeling can be used to predict airflow patterns and ammonia concentration distribution in a HRHB. The validation of the model can help to generate a deeper understanding of model fit.

- For an occupied animal facility, animal effects cannot be neglected. However, simple geometric models of lying or standing animals may allow the study of airflow in these buildings using CFD modeling.

- Turbulence models are often used in the CFD study of indoor airflow. RNG models show some improvement over standard $\kappa$-$\varepsilon$ models in predicting low Reynolds number ($2000 < \text{Re} < 1000$) airflow pattern.
CHAPTER 4

MATERIALS AND METHODS

Experiments were conducted at a commercial HRHB located in Darke County, OH (Figure 1-1). The house features wet dry feeders (Automated Production Systems Co.) and 48 pens containing 20 or 21 hogs per pen. Temperature is controlled using a Fancom climate controller (Fancom Co.) that automatically controls six 16-inch fans and twelve 36-inch fans as well as two electric heaters (unknown manufacturer). Two groups of hogs, 998 head in summer and 1047 head in winter were studied. Each was finished for about 120 days. Sawdust was used as porous bedding to accept manure and absorb liquid. The HRHB was visited every other week for sampling and ammonia measurement. The manure/bedding mixture was cleaned out after each production cycle and shipped to Fresh Air Farms where it was windrow composted. On one occasion, approximately 13% of the manure of the winter group was transported to Ohio Agricultural Research and Development Center (OARDC) for windrow composting.

4.1 Mass Balance

The mass balance approach included measurements of each major solid and liquid input and output from the HRHB and from an associated compost windrow (Figure 4.1).
Figure 4.1: Diagram of the mass flows through a High Rise Hog system and an associated windrow composting process.
Initial and final pig (and mortality) weights, total feed intake, and bedding material were included with appropriate conversions for total mass and dry matter, and total N, P and K. The total wet weight of the manure/bedding amendment was measured by weighting on a track-weighing wagon (unknown manufacturer) and characterized for moisture content and total N, P, and K at the OARDC soil testing and research (STAR) Lab, Wooster, OH.

(a) Hogs Feeder pigs (~20 kg) were obtained from Keller Grain and Feed, Inc. They were Monsanto Dekalb pigs. The number of pigs (including mortality and culls) were counted and weighed at the beginning and end of each production cycle. Livestock mortality dates and weights were also recorded. The nutrition data developed by Mahan and Shields (1998) were used to estimate the N, P, and K content of the pigs.

(b) Feed Feed was obtained from and prepared by Keller Grain and Feed, Inc. Initial and final feed weights were measured and feeds were analyzed for bulk density, moisture, ash, total N, total P, total K, protein, and total C content. Since swine were fed different feed rations for different phases of growth, dates and quantities of each feed mixture were recorded. Three samples of each feed were collected and analyzed by the OSU Soil Testing and Research (STAR) lab.

(c) Bedding, manure/bedding and composting materials Bedding, manure and composts were weighed using a truck weighing wagon (unknown manufacturer) as they were added to or removed from the production system. Four samples were collected at each weighing period for nutrient analysis. Homogenization of the bedding manure mixture via a compost windrow turner was performed prior to sampling. All materials
were analyzed for moisture, total N, total P, total K, total C, Ammonia-N, Nitrate-N, pH, bulk density, porosity, dry mass, and ash, as well as other nutrients and metals.

(d) Water  Water use was monitored in wet-dry feeders in the HRH building. Meters were read at the beginning and end of each cycle.

(e) Liquid drainage  Liquid drainage was sampled from the underground collection tank, where the runoff flowed to a 30 m x 40m pond. Samples were analyzed for total N, total P, total K, total C, Ammonia-N, Nitrate-N and pH.

(f) Others  Other measurements included indoor and outdoor air temperature and relative humidity, and the wind speed and direction. These measurements were taken during each visit. The manure was composted offsite at Fresh Air Farms (Greenville, OH). A windrow was constructed using a mixing wagon. It was 2.7 m x 1.0 m x 20.9 m (width x height x length). The windrows were turned twice in the first month, then once per other week using a windrow turner. Temperature and oxygen level at 1.5-3 feed depth in the compost windrow were monitored every two or three day using a digital thermometer and oxygen detector.

Collection of samples within the building and removal of animals or manure was done in compliance with OSHA requirements for safety. All experimental samples were placed in one-gallon Ziploc bags and transported from the field to the laboratory at OARDC within 24 hours of collection. All feeds and manure samples from the HRHB were analyzed by the Ohio State University Soil Testing and Research (STAR) Lab, Wooster, OH. Feed samples were placed in plastic bags and sealed. A minimum of 100 g of sample was collected.
Figure 4.2: Modeled region and ammonia measurement positions in the pig area viewed in the horizontal plane of a HRHB. The odd numbers represent the locations 4 feet high above the floor, and the even represent those 6 feet above the floor.
4.2 Air Quality-Ammonia Distribution

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 determine ammonia concentration within the building. Before the measurement, the reproducibility and reliability of diffusion tubes were tested using a calibration ammonia gas with concentration of 50 ppm (Appendix C). The measurement value was found to be in 80-120% of the expected value.

The diffusion tubes were suspended at four elevations; just above (1-5 cm) the manure storage area, 1.5 feet above the manure bedding, 4 feet above the slatted floor in the pig area, and 6 feet above the slatted floor in the pig area. Because the building is axially symmetrical, only two quadrants were chosen for ammonia measurements (Figure 4.2). Four positions in each quadrant were sampled to determine ammonia concentrations at specific points within the building (Figure 4.2). A pulley system designed by Michael Klingman and Roger Maas FABE, Wooster was used upstairs to transport the diffusion tubes to the measurement locations with no interference with the animals (Figure 4.3). Four fishing poles were used to suspend diffusion tubes over the manure storage area (Figure 4.3). These measurements were made every other week. Totally, six or seven groups of data were collected for each production cycle.
Figure 4.3: Pulley system and fishing poles used to transport diffusion tube to the measurement locations in HRHB
Figure 4.4: Exhaust fans and sampling positions (light dots) at the fan.
Short-term Dräger tubes (SKC Inc. 0.25-3 ppm and 2-30 ppm) and Dräger accuro® grab sample pump were used to measure ammonia concentrations at exhaust fans. The standard deviation of Dragger short time tubes provided by manufacturer is ± 10-15 % of measured value. Before each series of measurement, the accuro® pump was checked for leaks with an inserted unopened tube. The pump was adequately leak proof, if the end-of-stroke indicator had not appeared within fifteen minutes. When using short-term Dräger tubes, air or gas samples were sucked through the tube several times which depends on measurement requirement and tube limitation. The 0.25-3 ppm tube has a maximum stroke number of ten and the 2-30 ppm tube has that of five. In this study, to minimize the measurement bias and obtain accurate ammonia concentrations across the whole fan area, researchers took at least one stroke at 5 different positions of the fan (Figure 4.4).

4.3 CFD Modeling of Airflow and Ammonia Distribution in HRHB

GAMBIT® and FLUENT® 6 CFD software from FLUENT Inc., Lebanon, New Hampshire, were used to build a mathematical representation of an experimental HRHB and numerically solve the governing equations, including different forms of the Navier-Stokes equations, mass balance equations and energy balance equations, over a discretized flow field based on the finite volume method. In summer, 12 large fans ran frequently to keep the room temperature under 32°C which resulted in high air velocities at both ceiling inlet and outlet. Turbulent airflow patterns dominated in the building. However, during the minimum ventilation period in winter, resting, laminar, transient,
and turbulent flows co-exist in the building space. Reynolds numbers at the inlets and outlet were calculated based on the width of the channel inlet, the bedding area, and the diameter of outlet fans, as well as the averaged air velocities across its section (Table 4.1). The critical Reynolds number of 2000, at which transient flow becomes turbulent, was used to determine the airflow pattern through a plane channel (Lesieur, 1990). The calculation indicated that both laminar/transient and turbulent flow regions could simultaneously occur in this building under the minimum ventilation conditions in winter.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Inlet 1</th>
<th>Inlet 2</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Re&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1300&lt;sup&gt;b&lt;/sup&gt;</td>
<td>1800&lt;sup&gt;c&lt;/sup&gt;</td>
<td>1.6 x 10&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td>Flow</td>
<td>Laminar/transient</td>
<td>Laminar/transient</td>
<td>Turbulent</td>
</tr>
</tbody>
</table>

<sup>a</sup> Reynolds number = \( \frac{us}{\nu} \), where \( u \) is averaged velocity, \( s \) is specified length (see [b], [c] & [d] below), and \( \nu \) is kinetic viscosity.

<sup>b</sup> Based on the width of the channel inlet.

<sup>c</sup> Based on the width of the bedding that air passes through.

<sup>d</sup> Based on a diameter of small exhaust fan.

Table 4.1: Reynolds numbers at the inlets and outlet of HRHB under the minimum ventilation conditions.

However, CFD models that account for both laminar and turbulent flow are not currently available. In addition, the airflow in the HRHB was significantly affected by many factors such as room geometry, ventilation rate, animals, weather, fans, inlet baffles and humidity. It was difficult to directly develop a correct CFD model with appropriate
equations and boundary conditions. Therefore, a step-by-step modeling strategy was used in this study, which included three stages,

1. 2 dimensional laminar and turbulent models were developed to investigate airflow in the empty HRHB under the minimum ventilation conditions. No animal and energy balance were considered. The results were compared with preliminary measurements of ammonia concentrations and air velocity magnitudes in an unoccupied building. The model that most closely predicted ammonia measurements was used for the next-step study.

2. A 3-dimensional CFD model was developed to simulate airflow in the empty HRHB. The models were validated using the measurement data collected in an empty building.

3. A 3D non-isothermal model with animals was developed. Animals were simulated as several large boxes with constant surface temperatures. The CFD model was validated with in situ ammonia distribution and temperature data. The validated model was used for further study of airflow in the HRHB.

To simplify the modeling process, several assumptions were made. First, only a mixture of air and ammonia was considered in the model. The ammonia–air mixture was simulated as incompressible (under low pressure) and at continuous flow. Second, no chemical reactions or dispersed phase transportation was assumed to occur in the computational domain. Third, the computations were performed for steady state conditions.
4.3.1 Laminar flow model

Assuming that the flow is at steady state, there are no chemical reactions or dispersed phase transportation, and heating effects from the heaters, animals and walls are negligible, laminar flow governing equations apply (Bird et al., 1960), they are:

Conservation of mass:

\[ \frac{\partial}{\partial x_i} (\rho u_i) = 0 \]  

Conservation of momentum:

\[ \frac{\partial}{\partial x_j} (\rho u_i u_j) = -\frac{\partial P}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + \rho g_i + F_i \]  

where

- \( u = \) velocity
- \( \rho = \) fluid density
- \( P = \) static pressure
- \( \tau_{ij} = \) stress tensor
- \( g_i = \) gravitational acceleration
- \( F_i = \) external body force in the \( i \) direction. Here, \( F_i \) was negligible because the air velocities were relatively low.

The stress tensor \( \tau_{ij} \) was given by (Bird et al., 1960):

\[ \tau_{ij} = \left[ \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right] - \frac{2}{3} \mu \frac{\partial v_i}{\partial x_j} \delta_{ij} \]  

where \( \mu \) was the molecular viscosity. The effect of volume dilation was assumed to be negligible.
Conservation of species:

\[ \frac{\partial}{\partial x_i} (\rho u_i m_i') = -\frac{\partial}{\partial x_i} (J_{i',i}) \]  

(4)

where \( J_{i',i} \) was the diffusive mass flux of species \( i' \) in the \( i \)th direction, and \( m_i' \) was the mass fraction of species \( i' \). The summation of conservation equations for all the species present in the continuous phase equaled the overall mass conservation equation described earlier. Neglecting the thermal diffusion effect, \( J_{i',i} \) could be expressed as (Bird et al., 1960):

\[ J_{i',i} = -\rho D_{i',m} \frac{\partial m_i'}{\partial x_i} \]  

(5)

where \( D_{i',m} \) was the diffusion coefficient for species \( i' \) in the mixture.

The laminar flow equations were solved using the boundary conditions of the inlet velocities and concentrations, the outlet, and the solid surface boundary conditions (Table 4.2).

<table>
<thead>
<tr>
<th>Variables</th>
<th>Inlet 1</th>
<th>Inlet 2</th>
<th>Outlet</th>
<th>Wall boundary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity (m/s)</td>
<td>Specified</td>
<td>Specified</td>
<td>Outflow</td>
<td>Wall function(^\dagger)</td>
</tr>
<tr>
<td>Mass fraction (m) of NH(_3)</td>
<td>Specified</td>
<td>Specified</td>
<td>Mass balance</td>
<td>( \partial m/\partial y_p = 0 )*</td>
</tr>
<tr>
<td>(kg/kg)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(* y_p \) is the distance from point \( p \) to the wall,

\(^\dagger\) Details are shown in Chapter 6.13 of FLUENT 5.0 User Guide

Table 4.2. Boundary conditions defined for a CFD laminar-flow model of HRHB
4.3.2 Turbulent flow model

The turbulent flow model was based on the continuity equation, Reynolds-averaged Navier-stokes equation and concentration equations together with $\kappa$-$\varepsilon$ turbulence model equations (Ayad, 1999; Fan, 1995; Gan, 1995; Awbi, 1998; FLUENT, 1998; Lee & Short, 2000). Because the high frequency and small-scale fluctuations of turbulent flow could not be directly quantified, the instantaneous fluid velocity was assumed as the sum of a mean (ensemble-averaged or time-averaged) and a fluctuating turbulent velocity component. The Reynolds stresses were assumed to be proportional to the mean velocity gradients, with the constant of proportionality being the turbulent viscosity, $\mu_t$, also known as the Boussinesq hypothesis (Bird, 1960; Lee & Short, 2000). With these assumptions, the mass and momentum conservation equations were given by (Brodkey, 1967; Bird et al., 1960; FLUENT, 1998)

$$\frac{\partial}{\partial x_i} (\rho u_i) = 0$$  \hspace{1cm} (6)

$$\rho \frac{Du_i}{Dt} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left( \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \delta_{ij} \frac{\partial u_i}{\partial x_i} \right) - \rho u_i u_j' + \rho g_i + \text{F}_i \right)$$  \hspace{1cm} (7)

where $F_i$ contained other model-dependent source terms such as porous media sources.

The Reynolds stress (FLUENT, 1998) was:

$$-\rho u_i u_j' = \mu_t \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{2}{3} \left( \rho k + \mu_t \frac{\partial u_i}{\partial x_i} \right) \delta_{ij}$$  \hspace{1cm} (8)

where $\mu_t$ was turbulent viscosity, which was computed as a function of $k$ (turbulence kinetic energy) and $\varepsilon$ (the dissipation rate of turbulent kinetic energy).
The values of $k$ and $\varepsilon$ (FLUENT, 1998) were obtained through solving conservation equations defined by $\kappa$-$\varepsilon$ turbulence models. In this study, standard $\kappa$-$\varepsilon$ model (Launder and Spalding, 1972) and Renormalization-group (RNG) $\kappa$-$\varepsilon$ model (Yakhot et al., 1986) were used to simulate airflow in the HRHB. As mentioned in Chapter 3, the standard $\kappa$-$\varepsilon$ model was typically used in the simulation of airflow in greenhouses and animal facilities. The RNG model provides a more accurate simulation results for low ventilation conditions by using an analytically derived differential formula for effective viscosity, which accounts for low-Reynolds-number effects (Yakhot and Orszag, 1986; FLUENT, 1998). However, the RNG model often experiences convergence difficulties (FLUENT, 1998). In order to achieve better convergence, the standard $\kappa$-$\varepsilon$ model was usually used to obtain a solution and this solution used as input to the RNG model. Furthermore, the RNG model provides a similar formula to calculate the turbulent velocity in the high Reynolds number limit. Therefore, both standard and RNG models were used in this study.

The standard $\kappa$-$\varepsilon$ model had two equations,

$$ \rho \frac{Dk}{Dt} = \frac{\partial}{\partial x_i} \left( \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_i} \right) + G_k + G_b + \varepsilon - \rho \varepsilon - Y_M $$ (9)

$$ \rho \frac{De}{Dt} = \frac{\partial}{\partial x_j} \left( \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial e}{\partial x_j} \right) + C_{1e} \frac{e}{k} (G_k + C_{3e} G_b) - C_{2e} \rho \frac{e^2}{k} $$ (10)

where $G_k$ (FLUENT, 1998) represented the generation of turbulent kinetic energy due to the mean velocity gradients, $G_b$ was the generation of turbulent kinetic energy due to buoyancy, $Y_M$ represented the contribution of the fluctuating dilation in compressible
turbulence to the overall dissipation rate that was neglected in this study. $C_{2e}$ represented the degree to which $\varepsilon$ was affected by the buoyancy effects. The calculation of these parameters is described in the Fluent User Guide (FLUENT, 1998). The turbulent viscosity $\mu_t$ was calculated by

$$\mu_t = \rho C_{\mu} \frac{k^2}{\varepsilon}$$

(11)

$C_{\mu}$, $C_{1e}$, $C_{2e}$, $\sigma_k$, $\sigma_\varepsilon$ were constants with the following values (Launder and Spalding, 1974; Ayad, 1999):

$$C_{\mu} = 0.09, \quad C_{1e} = 1.44, \quad C_{2e} = 1.92, \quad \sigma_k = 1.0, \quad \sigma_\varepsilon = 1.3$$

(12)

Renormalization-group (RNG) $\kappa$-$\varepsilon$ model also had two equations,

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

(13)

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

(14)

where

$$\mu_{\text{eff}} = \mu + \mu_t$$

(15)

$\alpha_k$ and $\alpha_\varepsilon$ were the inverse effective Prandtl numbers for $\kappa$ and $\varepsilon$, respectively. The $R$ term was responsive to the effect of rapid strain and streamline curvature (FLUENT, 1998)

At the low Reynolds number, the turbulent viscosity $\mu_t$ was calculated by a differential equation:
\[ d \left( \frac{\rho^2 k}{\sqrt{\varepsilon \mu}} \right) = 1.72 \frac{\dot{v}}{\sqrt{\dot{v}^3 - 1 + C_v}} d \dot{v} \] \hspace{1cm} (16)

\[ \dot{v} = \frac{\mu_{\text{eff}}}{\mu} ; \quad C_v \approx 100. \]

In the high-Reynolds-number limit,

\[ \mu_t = \rho C_{\mu} \frac{k^2}{\varepsilon} \] \hspace{1cm} (17)

which is same as that in standard \( \kappa-\varepsilon \) model except \( C_{\mu} = 0.0845 \).

The constants \( C_{1\varepsilon}, C_{2\varepsilon} \) had the following values (FLUENT, 1998):

\( C_{1\varepsilon} = 1.42, C_{2\varepsilon} = 1.68. \)

The turbulent flow equations were solved using the boundary conditions of the inlet velocities and concentrations, the outflow, the solid surface boundary conditions and turbulent properties. (Table 4.3)
<table>
<thead>
<tr>
<th>Variables</th>
<th>Inlet 1</th>
<th>Inlet 2</th>
<th>Outlet</th>
<th>Wall Boundary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity (m/s)</td>
<td>Specified V</td>
<td>Specified V</td>
<td>Outflow</td>
<td>Wall function</td>
</tr>
</tbody>
</table>
| Mass fraction (m) of NH3 (kg/kg)  | Specified m | Specified m | Mass balance | \( \frac{\partial m}{\partial y_p} = 0 \)

\[
k = \frac{3}{2} \left( u_{avg} l \right)^2 \quad \varepsilon = \frac{c_u^{0.75} k^{1.5}}{0.07 L} \quad \varepsilon = \frac{c_u^{0.75} k^{1.5}}{0.07 L} \quad \varepsilon = \frac{c_u^{0.75} k^{1.5}}{0.419 y_p} \quad \varepsilon = 0 \text{ on wall}
\]

\( I \) is the turbulence intensity. \( I \) equals 0.1%. (FLUENT, 1998)

\( L \) is the length scale.

\( k_p \) is turbulent kinetic energy at point P.

\( y_p \) is the distance from point p to wall.

Table 4.3: Initial and boundary conditions defined for a CFD turbulent-flow model of HRHB
4.3.3 Energy balance equations

When hogs were simulated in the CFD model, heat transfer processes were added to the model. The energy balance governing equation was

\[
\frac{\partial}{\partial t}(\rho E) + \frac{\partial}{\partial x_i}(u_i (\rho E + p)) = \frac{\partial}{\partial x_i}\left( k_{\text{eff}} \frac{\partial T}{\partial x_i} - \sum_{j'} h_{j'} J_{j'} + u_i (\tau_{ij})_{\text{eff}} \right) + S_h \tag{17}
\]

\(E\) is the total energy,

\[
E = h - \frac{p}{\rho} + \frac{u_i^2}{2} \tag{18}
\]

where sensible enthalpy \(h\) is defined for incompressible gases as

\[
h = \sum_{j'} m_{j'} h_{j'} + \frac{p}{\rho} \tag{19}
\]

\(m_{j'}\) is the mass fraction of gas species and

\[
h_{j'} = \int_{T_{\text{ref}}}^T c_{p,j'} dT \tag{20}
\]

where \(T_{\text{ref}}\) is 298.15 K, \(C_{p,j'}\) is the heat capacity of the species \(j'\), \(T\) is temperature, \(k_{\text{eff}}\) is the effective conductivity depending on to the physical model being used (Fluent, 1998), and \(h_{j'}\) is the enthalpy of the species \(j'\). \(J_{j'}\) is the diffusion flux of species \(j'\). \((\tau_{ij})_{\text{eff}}\) represents the viscous heating, which was negligible since the viscosity of air was low and air velocity was not very high \((v < 8 \text{ m/s})\). \(S_h\) includes heat of any defined volumetric heat sources.
The first three terms on the right-hand side of the energy balance equation represents energy transfer due to conduction, species diffusion, and viscous dissipation, respectively. It was solved using the boundary conditions of the inlet temperature, the outflow, wall temperature and the convective heat transfer on solid surface (Table 4.4)

<table>
<thead>
<tr>
<th>Variables</th>
<th>Inlet 1</th>
<th>Inlet 2</th>
<th>Outlet</th>
<th>Side Wall</th>
<th>Animal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (K)</td>
<td>Specified</td>
<td>Specified</td>
<td>NA</td>
<td>NA</td>
<td>Specified</td>
</tr>
<tr>
<td>Heat transfer coefficient (w/m²)</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>Determined using the structure materials parameters provided by ASHRAE, (2000)</td>
<td>NA</td>
</tr>
<tr>
<td>Thickness (m)</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>Specified</td>
<td>Specified</td>
</tr>
<tr>
<td>Free Stream Temperature (K)</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>Specified</td>
<td>NA</td>
</tr>
</tbody>
</table>

NA=not available

Table 4.4: Thermal boundary conditions defined for a CFD turbulent-flow model of an occupied HRHB
4.3.4 HRHB configurations and boundary conditions

The dimensions and operating conditions of a commercial HRHB located in Darke County, Ohio (Figure 1.1) were used to generate the CFD model. This two-level building was 13.7 m wide, 71.1 m long and 7.72 m high. Each level had an indoor height of 2.44 m. Fresh air (without ammonia) entered the upper level of this building from the attic through a baffled center ceiling inlet (Inlet 1) (Figure 1.1). It mixed with building air and moved down through the slatted floor to the lower level, which had a manure bed of 1-2 feet. Air was also blown into the building from below the bedding through the manure mixture via a fan and manifold system (inlet 2) (Figure1.1). All air was exhausted through the outlets in the sidewalls of the lower story. The ventilation conditions varied summer and winter conditions. Six 0.406 m (diameter) fans were used under the winter minimum ventilation condition to conserve heat. Twelve 0.914 m (diameter) fans were used for cooling in the hot summer conditions. A representative section of the HRHB was simulated based on the geometrical arrangement of the exhaust fans (Figure 4.2). It was 6.8 m wide and 4.4 m high. The length was about 11 m for winter conditions and 5 m for summer conditions, respectively (Figure 4.5)

As mentioned above, this study included three stages, these being 2-dimensional isothermal model for empty HRHB, 3-dimensional isothermal model for empty HRHB and 3-dimensional non-isothermal model for animal occupied HRHB. The appropriate simplification and boundary conditions for each stage were described in following sections
Figure 4.5: Building and hog body representation for modeling purposes and geometry used for CFD modeling for a High-Rise™ hog building
4.3.4.1 2-dimensional model

Only winter conditions were simulated using 2-D model. One complexity of modeling a HRH with a 2D model was that while the slot ceiling inlet and floor air inlet could both be accurately modeled with a 2D model, the fan outlet could be better modeled using a 3D model. However, 3D CFD models were complex and required extensive computing time. The 2D model, while not ideal, gave valuable information about the air velocity profiles and ammonia concentration in the building. By simplifying the geometry and conditions to 2-dimensions, a solution was obtained in a reasonable amount of time. This approach was not unprecedented. In a previous study, Wood et al. (1998) used a 2-D CFD model to simulate hydrodynamic flows in a waste stabilization pond where the inlet and outlet pipes were of similar geometry to the fan outlet in our model and were assumed to be over the full height of their models.

The floor of the pig area had slots of 2.5 cm (1 inch) every 18 cm (7 inches). This floor system was simplified for modeling purposes as a porous media with a porosity of 0.14. The exhaust fan was simulated as a narrow gap of 0.69 cm, which extended the length of the building, with the same outlet area and mean airflow velocity as the true fan system (Figure 4.6). The CFD grid used in the model is shown in Figure 4.7. Totally, about 10,000 grids were used.
Figure 4.6: Geometry used for 2-D CFD modeling for HRHB
Figure 4.7: Grid used for computational fluid dynamic modeling for a High-Rise™ Hog Building
The simulation considered both air velocity vectors and ammonia concentrations. The ammonia concentration at the aeration plenum (Inlet 2) was based on a previously reported value of 70 ppm in the winter of 1999 (Stowell et al., 1999). Fresh air without ammonia entered the upper story through center ceiling inlets (Inlet 1). The airflow velocities at the exhaust fan (Outlet; Fig. 2) and Inlet 2 were 8.8 m/s and 4.1 cm/s, respectively, based on the designed fan performance (Keener et al., 1999). The airflow velocity at Inlet 1 was 9.1 cm/s according to the mass continuity equation. In both models, the airflow velocity profile at Inlet 2 was considered to be uniform with the direction perpendicular to the floor surface (Figure 4.6).

The walls were modeled as standard walls using the wall function in the FLUENT program (Patankar, 1981; FLUENT, 1998). In the upper level, the walls were assumed as smooth walls with roughness heights of zero, and, in the lower level, a concrete roughness height of 0.5 mm and roughness constant of 0.5 were used. A range of values for the parameters $k$ and $\varepsilon$ were provided based on values used previously (Ayad, 1999; Fan, 1995; Launder and Spalding, 1974; FLUENT, 1998). The simulation results were compared to measurements made in 1999 (Stowell, 1999) and in 2001. The equations to specify these initial and boundary conditions are summarized in Table 4.5.
Table 4.5: Boundary conditions defined for a CFD laminar-flow model of HRHB

<table>
<thead>
<tr>
<th>Variables</th>
<th>Inlet 1</th>
<th>Inlet 2</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity (m/s)</td>
<td>0.091</td>
<td>0.004</td>
<td>Outflow</td>
</tr>
<tr>
<td>Mass fraction (m) of NH₃ (kg/kg)</td>
<td>0</td>
<td>0.000041</td>
<td>NA</td>
</tr>
</tbody>
</table>

4.3.4.2 3-dimensional isothermal model for empty HRHB

The three-dimensional model allows a more accurate representation of the exhaust fans and room geometry. The slatted floor was 0.1 m thick and 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 based on superficial velocity. Velocity was calculated using the predicted pressure drop through the slatted floor (Appendix C).

Both summer and winter conditions were modeled. The CFD grid used in the model is shown in Figure 4.9. Totally, about 160,000 grids were used. The wall was modeled as the same boundary condition used in 2-D model. However, the inlet airflow velocities and ammonia concentrations had been measured different from the designed parameters and previously reported value in an empty HRHB. Keener et al. (2000) had reported that exhaust fan efficiency dropped about 25% during the operation. Air velocities at both ceiling inlet and exhaust fans were measured using hotwire anemometer
(Figure 4.4). The pressure through the aeration systems to dry the manure was measured using a liquid column manometer. The airflow velocity through the inlet 2 was estimated by using pressure drop and fan curve provided by Keener et al. (2000).

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 equaled that in the bed (Bird et al., 1960) (Figure 4.8). Average airflow velocities and ammonia concentrations at inlets were used as boundary conditions in the model (Table 4.6)

![Diagram of airflow through manure mixture bed](image)

Assumption: $C_{\text{leaving}} = C_p$

Figure 4.8 Assumption used at inlet 2 to simulate airflow through manure mixture bed
Figure 4.9: Grid used for computational fluid dynamic modeling for a High-Rise™ hog building (Winter condition).
<table>
<thead>
<tr>
<th></th>
<th>Summer</th>
<th>Winter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fan size (diameter) (m)</td>
<td>0.914</td>
<td>0.406</td>
</tr>
<tr>
<td>Gap size of the baffle (m)</td>
<td>0.080</td>
<td>0.006</td>
</tr>
<tr>
<td>Ceiling Inlet (Inlet 1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air velocity (m/s)</td>
<td>2.20</td>
<td>0.16</td>
</tr>
<tr>
<td>Ammonia concentration (ppm)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Turbulence intensity (I)</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Turbulence length scale (L) (m)</td>
<td>0.0142</td>
<td>0.0142</td>
</tr>
<tr>
<td>Inlet 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air velocity (m/s)*</td>
<td>0.002</td>
<td>0.002</td>
</tr>
<tr>
<td>Ammonia concentration (ppm)</td>
<td>25</td>
<td>42</td>
</tr>
<tr>
<td>Turbulence intensity (I)</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Turbulence length scale (L) (m)</td>
<td>0.67</td>
<td>0.67</td>
</tr>
<tr>
<td>Walls surface</td>
<td>Standard</td>
<td>Standard</td>
</tr>
</tbody>
</table>

The initial turbulent kinetic energy ($\kappa$) and dissipation rate of turbulent kinetic energy ($\varepsilon$) at the inlets were computed using the functions given by FLUENT (1998).

* average airflow velocity

Table 4.6: The initial and boundary conditions used in 3-D isothermal CFD model for both summer and winter conditions.
4.3.4.3 3-dimensional non-isothermal model for an animal occupied HRHB

Two groups of Hogs were grown in the building with an initial average weight of 20 kg (45 lbs) between June 2002 and March 2004 (998 heads in summer and 1047 heads in winter). After 120 days, they were moved from the building with an average weight of 120 kg (265 lbs). In the model, hogs with an average weight of 70 kg (155 lbs) were simulated as boxes with dimensions of 30 by 45 by 90 cm, which was estimated using the measurement data provided by Ted Wiseman. The animal surface temperature was measured as $37 \pm 1^\circ C$ using an infrared temperature probe. It was assumed that the animal’s shape did not significantly affect the overall airflow pattern in the building.

The CFD grid used in the model is shown in Figure 4.10. Totally, about 200,000 grids were used. The wall was modeled as standard wall with a convective heat transfer boundary condition. During the operation, farmers used an intermittent aeration strategy to dry the manure. Therefore, to simulate the aeration and non-aeration conditions, two different boundary conditions were used at inlet 2, one was velocity inlet which was similar to that used in isothermal model and the other was a wall boundary conditions. While the aeration system was off, ammonia concentration on the surface of manure bedding was calculated based on the measured ammonia nitrogen content in manure/bedding material and two equilibriums of chemical reaction and phase change (appendix A). Average airflow velocities, temperature and ammonia concentrations at inlets were used as boundary conditions in the model (Table 4.7 & 4.8)
Case 1: No aeration through manure bedding  | Case 2: aeration through manure bedding
--- | ---
Fan size (diameter) (m) | 0.914 | 0.914
Gap size of the baffle (m) | 0.1 | 0.1
Ceiling Inlet (Inlet 1)  
  Air velocity (m/s) | 2.40 | 2.40
  Ammonia concentration (ppm) | 0 | 0
  Temperature (K) | 301 | 301
  Turbulence intensity (I) | 0.01 | 0.01
  Turbulence length scale (L) (m) | 0.0142 | 0.0142
Inlet 2  
  Wall boundary | Yes | No
  Air velocity (m/s)* | 0 | 0.002
  Ammonia concentration (ppm) | 100 | 25
  Temperature (K) | 300 | 300
  Turbulence intensity (I) | 0.01 | 0.01
  Turbulence length scale (L) (m) | 0.67 | 0.67
Hogs surface  
  Temperature (K) | 310 | 310

The initial turbulent kinetic energy ($\kappa$) and dissipation rate of turbulent kinetic energy ($\epsilon$) at the inlets were computed using the functions given by FLUENT (1998).

* average airflow velocity

Table 4.7: The initial and boundary conditions used in 3-D non-isothermal CFD model for summer conditions.
<table>
<thead>
<tr>
<th></th>
<th>Case 1 No aeration through manure bedding</th>
<th>Case 2 aeration through manure bedding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fan size (diameter) (m)</td>
<td>0.406</td>
<td>0.406</td>
</tr>
<tr>
<td>Gap size of the baffle (m)</td>
<td>0.006</td>
<td>0.006</td>
</tr>
<tr>
<td>Ceiling Inlet (Inlet 1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air velocity (m/s)</td>
<td>0.16</td>
<td>0.16</td>
</tr>
<tr>
<td>Ammonia concentration (ppm)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Temperature (K)</td>
<td>273</td>
<td>273</td>
</tr>
<tr>
<td>Turbulence intensity (I)</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Turbulence length scale (L) (m)</td>
<td>0.0142</td>
<td>0.0142</td>
</tr>
<tr>
<td>Inlet 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wall boundary</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Air velocity (m/s)*</td>
<td>0</td>
<td>0.002</td>
</tr>
<tr>
<td>Ammonia concentration (ppm)</td>
<td>100</td>
<td>42</td>
</tr>
<tr>
<td>Temperature (K)</td>
<td>290</td>
<td>290</td>
</tr>
<tr>
<td>Turbulence intensity (I)</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Turbulence length scale (L) (m)</td>
<td>0.67</td>
<td>0.67</td>
</tr>
<tr>
<td>Hogs surface</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature (K)</td>
<td>310</td>
<td>310</td>
</tr>
</tbody>
</table>

The initial turbulent kinetic energy ($\kappa$) and dissipation rate of turbulent kinetic energy ($\varepsilon$) at the inlets were computed using the functions given by FLUENT (1998).

* average airflow velocity

Table 4.8: The initial and boundary conditions used in 3-D non-isothermal CFD model for winter conditions.
Figure 4.10: Grid used for 3-D non-isothermal modeling for a High-Rise™ hog building (Winter condition)
4.4 Validation of CFD model

The validation experiments were made for each model because of the different situations simulated by models and different boundary conditions used in the model. Based on the ammonia concentration profile predicted by the 2-D models, three sampling locations in the cross section of the building were selected to validate the models (Figure 4.11). At each location, three measurements were made using Dräger diffusion tubes, which were evenly distributed over the 3-D hog space (Figure 4.12).

![Diagram of ammonia measurement locations viewed in a cross-section plane for validation of 2-D CFD model made in 2000.](image)

Figure 4.11: Ammonia measurement locations viewed in a cross-section plane for validation of 2-D CFD model made in 2000.
Figure 4.12: Ammonia measurement locations viewed in a horizontal plane for validation of 2-D CFD model made in 2000.
The validation experiment in empty HRHB was made with all exhaust fans manually controlled to provide a fixed ventilation rate out of the building. Averaged airflow velocities ammonia concentrations at inlets were used as boundary conditions in the model (Table 4.9).

The experiments were performed three days after hogs were moved out of the building. Since no more fresh urea and feces fell onto the top the storage area, the surface of the manure/bedding appeared dryer than usual. The average ammonia concentration at inlet 2 was lower than that measured while the hogs were grown upstairs. Therefore, the boundary conditions in the model were adjusted to account for this change (Table 4.9). Ammonia diffusion tubes were suspended at two elevations; 4 feet above the slatted floor in the pig area, and 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 4.13). Each measurement was repeated at least twice.
<table>
<thead>
<tr>
<th></th>
<th>Summer</th>
<th>Winter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fan size (diameter) (m)</td>
<td>0.914</td>
<td>0.406</td>
</tr>
<tr>
<td>Gap size of the baffle (m)</td>
<td>0.080</td>
<td>0.006</td>
</tr>
<tr>
<td>Ceiling Inlet (Inlet 1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air velocity (m/s)</td>
<td>2.20</td>
<td>0.16</td>
</tr>
<tr>
<td>Ammonia concentration (ppm)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Turbulence intensity (I)</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Turbulence length scale (L) (m)</td>
<td>0.0142</td>
<td>0.0142</td>
</tr>
<tr>
<td>Inlet 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air velocity (m/s)*</td>
<td>0.002</td>
<td>0.002</td>
</tr>
<tr>
<td>Ammonia concentration (ppm)</td>
<td>17</td>
<td>25</td>
</tr>
<tr>
<td>Turbulence intensity (I)</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Turbulence length scale (L) (m)</td>
<td>0.67</td>
<td>0.67</td>
</tr>
</tbody>
</table>

The initial turbulent kinetic energy ($\kappa$) and dissipation rate of turbulent kinetic energy ($\epsilon$) at the inlets were computed using the functions given by FLUENT (1998).

* average airflow velocity

Table 4.9. The initial and boundary conditions used in validation of CFD model for both summer and winter conditions.
Figure 4.13: Ammonia measurement locations viewed in a horizontal plane (a) for summer condition and (b) for winter condition.
The validation experiments in occupied HRHB were made four times during the pig mid-growth period (≈ 60 days) with the indoor temperature maintained around 18°C. The room temperature was usually 4 °C higher than this level during the first few weeks of growth and about 1-2°C lower than this level in the last few weeks.

Ammonia concentrations were measured every other week. Temperature was continuously measured using a thermocouple system in the HRHB. The measurements in the pig area were made at the same positions as those for ammonia measurement (Figure 4.2). The temperature on the manure/bedding surface was periodically measured using an infrared meter.

Since the outdoor temperature could affect ammonia concentration in HRHB, three different temperature levels of -5, 0 and 5°C in winter as well as 28 and 32°C in summer at ceiling inlet were simulated and compared with the actual measurement (Table 4.10 & 4.11). A two way ANOVA statistical model was used to analysis the difference between model predictions and measurements as well as the effect of measurement locations across the pig space.
<table>
<thead>
<tr>
<th></th>
<th>Case 1-2, No aeration through manure bedding</th>
<th>Case 3-4 aeration through manure bedding</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Fan size (diameter) (m)</td>
<td>0.914</td>
<td>0.914</td>
</tr>
<tr>
<td>Gap size of the baffle (m)</td>
<td>0.100</td>
<td>0.100</td>
</tr>
<tr>
<td>Ceiling Inlet (Inlet 1)</td>
<td>Air velocity (m/s)</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td>Ammonia concentration (ppm)</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Temperature (K)</td>
<td>301</td>
</tr>
<tr>
<td></td>
<td>Turbulence intensity (I)</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>Turbulence length scale (L) (m)</td>
<td>0.0142</td>
</tr>
<tr>
<td>Inlet 2</td>
<td>Wall boundary</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Air velocity (m/s)*</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Ammonia concentration (ppm)</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>Temperature (K)</td>
<td>298</td>
</tr>
<tr>
<td></td>
<td>Turbulence intensity (I)</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>Turbulence length scale (L) (m)</td>
<td>0.67</td>
</tr>
<tr>
<td>Hogs surface</td>
<td>Temperature (K)</td>
<td>310</td>
</tr>
</tbody>
</table>

The initial turbulent kinetic energy ($\kappa$) and dissipation rate of turbulent kinetic energy ($\varepsilon$) at the inlets were computed using the functions given by FLUENT (1998).

* average airflow velocity

Table 4.10: The initial and boundary conditions used in validation of the non-isothermal CFD model for summer conditions.
<table>
<thead>
<tr>
<th>Case 1-3, No aeration through manure bedding</th>
<th>Case 4-6 aeration through manure bedding</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Fan size (diameter) (m)</td>
<td>0.406</td>
</tr>
<tr>
<td>Gap size of the baffle (m)</td>
<td>0.006</td>
</tr>
<tr>
<td>Ceiling Inlet (Inlet 1)</td>
<td></td>
</tr>
<tr>
<td>Fan size (diameter) (m)</td>
<td>0.406</td>
</tr>
<tr>
<td>Gap size of the baffle (m)</td>
<td>0.006</td>
</tr>
<tr>
<td>Air velocity (m/s)</td>
<td>0.16</td>
</tr>
<tr>
<td>Ammonia concentration (ppm)</td>
<td>0</td>
</tr>
<tr>
<td>Temperature (K)</td>
<td>268</td>
</tr>
<tr>
<td>Turbulence intensity (I)</td>
<td>0.01</td>
</tr>
<tr>
<td>Turbulence length scale (L) (m)</td>
<td>0.0142</td>
</tr>
<tr>
<td>Inlet 2</td>
<td></td>
</tr>
<tr>
<td>Wall boundary</td>
<td>Yes</td>
</tr>
<tr>
<td>Air velocity (m/s)*</td>
<td>0</td>
</tr>
<tr>
<td>Ammonia concentration (ppm)</td>
<td>100</td>
</tr>
<tr>
<td>Temperature (K)</td>
<td>290</td>
</tr>
<tr>
<td>Turbulence intensity (I)</td>
<td>0.01</td>
</tr>
<tr>
<td>Turbulence length scale (L) (m)</td>
<td>0.67</td>
</tr>
<tr>
<td>Hogs surface</td>
<td></td>
</tr>
<tr>
<td>Temperature (K)</td>
<td>310</td>
</tr>
</tbody>
</table>

The initial turbulent kinetic energy ($\kappa$) and dissipation rate of turbulent kinetic energy ($\varepsilon$) at the inlets were computed using the functions given by FLUENT (1998).

*average airflow velocity

Table 4.11: The initial and boundary conditions used in validation of the non-isothermal CFD model for winter conditions.
4.5 Modification of Ventilation System

During the minimum ventilation period, ammonia measured high in the upper level of the building. In order to minimize the ammonia concentration in the pig space, the ventilation system or operation strategies might be optimized. The aeration used to dry the manure in the lower level of the building probably had a potential to carry some ammonia to the upper level of building. Using CFD model could be an efficient method to investigate the effect of aeration on ammonia distribution in the pig space. In this study, the two aeration conditions from beneath the manure bedding were simulated in two non-isothermal CFD models, 1.an air velocity of 2 mm/s and 2.no aeration.

The baffled ceiling inlet size could also significantly affect the inlet airflow velocity, which resulted in different airflow patterns in the upper level of the building as well as the ammonia distribution in the pig space. To study the effect of ceiling inlet size, 3-dimensional non isothermal CFD models were used to simulated two gap sizes of 0.006 m and 0.04 m, which represent the typical inlet size used in winter and summer, respectively.

Exhaust fans’ location and numbers could be another significant factor to influence airflow pattern in animal space. Ammonia had been found not evenly distributed in the pig area. In order to achieve better air quality, more fans were simulated in the building with the same air change rate of 5 air change per hour.
CHAPTER 5

RESULTS AND DISCUSSION

5.1 Nutrient Mass Balance around HRHB system

5.1.1 Animal performance and economic analysis

For the nutrient mass balance analysis, finishing hogs were grown in a HRHB during summer and winter of 2002. Animals in both the summer and winter groups grew well with an average weight gain rate of 0.85 kg/pig/day (1.89 lb/pig/day) (Table 5-1, 5-2). The feed was consumed at a rate of 2.4 kg/pig/day (5.3 lb/pig/day). The average conversion ratio of feed was about 2.83, which compares to a mean conversion ratio of 3.28 recommended by Losinger (1998) and the 3.04 conversion ratio for Hoop Structures presented by Honeyman et al. (2001). The winter group had a higher weight gain rate (0.86 kg/pig/day) and lower feed conversion rate of 2.84 as compared to the summer group. The winter group also experienced half the mortality rate compared to the summer group (1.6% in winter vs. 3.5% in summer). This may have been due to heat stress in summer condition.

The energy used for heating, light and fan operation in the HRH system was 17,230 kwh at a cost of $1120 in the winter and 17,953 kwh at a cost of $1167 in the summer. During the summer period, twelve large fans ran frequently to cool the building, resulting in more electric energy use in summer than in winter. However, the
Table 5.1. Summary of the major solid and liquid inputs and outputs from the HRHB during the summer of 2002.

<table>
<thead>
<tr>
<th></th>
<th>Initial Input (5/28/02)</th>
<th>Final Output* (9/27/02)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>U.S. Units</td>
<td>Metric Units</td>
</tr>
<tr>
<td><strong>Hogs</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average weight</td>
<td>45 lb</td>
<td>20.4 kg</td>
</tr>
<tr>
<td>Total number</td>
<td>998</td>
<td>998</td>
</tr>
<tr>
<td><strong>Mortality</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average weight</td>
<td></td>
<td>148 lb</td>
</tr>
<tr>
<td>Total number</td>
<td></td>
<td>35</td>
</tr>
<tr>
<td><strong>Feed</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total weight</td>
<td>296 ton</td>
<td>268 ton</td>
</tr>
<tr>
<td>Average weight (/pig/day)</td>
<td>5.2 lb</td>
<td>2.36 kg</td>
</tr>
<tr>
<td><strong>Bedding</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Sawdust + shavings)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total weight</td>
<td>44.8 ton</td>
<td>40.6 ton</td>
</tr>
<tr>
<td>Average weight (/pig)</td>
<td>89.7 lb</td>
<td>40.7 kg</td>
</tr>
<tr>
<td><strong>Manure bedding</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total weight</td>
<td></td>
<td>121 ton</td>
</tr>
<tr>
<td>Average weight (/pig)</td>
<td>242 lb</td>
<td>110 kg</td>
</tr>
<tr>
<td><strong>Water use</strong></td>
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<td></td>
</tr>
<tr>
<td>Total volume</td>
<td>161209 gal</td>
<td>6101 m³</td>
</tr>
<tr>
<td>Average volume (/pig/day)</td>
<td>1.35 gal</td>
<td>5.1 l</td>
</tr>
<tr>
<td></td>
<td>Initial Input (10/15/02)</td>
<td>Final Output* (2/19/03)</td>
</tr>
<tr>
<td>----------------------</td>
<td>--------------------------</td>
<td>-------------------------</td>
</tr>
<tr>
<td></td>
<td>U.S. Units</td>
<td>Metric Units</td>
</tr>
<tr>
<td><strong>Hogs</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average weight</td>
<td>47 lb</td>
<td>21.3 kg</td>
</tr>
<tr>
<td>Total number</td>
<td>1047</td>
<td>1047</td>
</tr>
<tr>
<td><strong>Mortality</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average weight</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total number</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Feed</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total weight</td>
<td>325 ton</td>
<td>294.8 ton</td>
</tr>
<tr>
<td>Average weight (/pig/day)</td>
<td>5.2 lb</td>
<td>2.45 kg</td>
</tr>
<tr>
<td><strong>Bedding</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Sawdust + shavings)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total weight</td>
<td>55 ton</td>
<td>50 ton</td>
</tr>
<tr>
<td>Average weight (/pig)</td>
<td>105 lb</td>
<td>47 kg</td>
</tr>
<tr>
<td><strong>Manure bedding</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total weight</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average weight (/pig)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Water use</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total volume</td>
<td>158347 gal</td>
<td>5993 m³</td>
</tr>
<tr>
<td>Average volume (/pig/day)</td>
<td>1.26 gal</td>
<td>4.8 l</td>
</tr>
</tbody>
</table>

* market day

Table 5.2. Summary of the major solid and liquid inputs and outputs from the HRHB during the winter of 2003
energy use difference was only 723 kwh. Two electric heaters above hog space were
turned on when the room temperature was lower than 15°C adding to fan energy use in
winter.

The propane used for heating was 2833 gal (approximate $170) in winter and
1278 gal (approximate $77) in summer. The large increase from the summer to the winter
was due to the heat requirement in winter to maintain operation room temperatures above
17°C and hot water needed for worker’s bath.

Labor costs were for a farm worker to visit the building twice per day, in the
morning and in the afternoon for one hour. The worker’s duties included cleaning the
aisle and moving the dead or ill animals away from others. For each production cycle,
about 1000 hogs were loaded into the building on the first day. This process usually took
a half-day. After 118 days, hogs were gradually removed to market. A bobcat loader was
used to remove manure from the building, which was transported to a composting site
directly. In this study, an average of 8 transportations were used after a production cycle,
which in total cost approximately $800. The manure was composted offsite at Fresh Air
Farms located 30 miles form the HRHB. The windrows were turned twice in the first
month, then once per other week using a windrow turner. The final compost was sold for
a price ranging from $12-18 based on the quality of the compost (raw or screened
product).

5.1.2 Nitrogen, phosphorous and potassium losses from the HRH building

At the start of the experiment, sawdust bedding was added at a rate of 45 kg/pig
to absorb the moisture from the manure in the lower story. The bedding depth ranged
<table>
<thead>
<tr>
<th></th>
<th>Inputs</th>
<th>Outputs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pigs b</td>
<td>Feed a, d, e</td>
</tr>
<tr>
<td>Summer group</td>
<td>pH</td>
<td>5.69±0.07</td>
</tr>
<tr>
<td></td>
<td>Total solid %</td>
<td>88.8±0.04</td>
</tr>
<tr>
<td></td>
<td>Ash %</td>
<td>4.34±0.11</td>
</tr>
<tr>
<td></td>
<td>Total N (%)</td>
<td>2.37 c</td>
</tr>
<tr>
<td></td>
<td>Total P (ug/g)</td>
<td>5400</td>
</tr>
<tr>
<td></td>
<td>Total K (ug/g)</td>
<td>929.6</td>
</tr>
<tr>
<td>Winter group</td>
<td>pH</td>
<td>5.91±0.01</td>
</tr>
<tr>
<td></td>
<td>Total solid %</td>
<td>88.5±0.13</td>
</tr>
<tr>
<td></td>
<td>Ash %</td>
<td>5.4±0.114</td>
</tr>
<tr>
<td></td>
<td>Total N (%)</td>
<td>2.37 c</td>
</tr>
<tr>
<td></td>
<td>Total P (ug/g)</td>
<td>5400</td>
</tr>
<tr>
<td></td>
<td>Total K (ug/g)</td>
<td>929.6</td>
</tr>
</tbody>
</table>

The error is the standard error. The error of feed is calculated based on 5 different types of feed material, each has three samples.

a Sample supplied by Keller Grain and Feed Inc.
b Based on live weight (Mahan and Shields, 1998)
c Based on the assumption that the nitrogen content in protein is about 16%
d Based on the dry weight.
e Based on the total feed weight

Table 5.3: Nutrient content of the major inputs and outputs from the HRHB.
from 20 cm to 30 cm. During growth, manure accumulated at an average rate of 0.63 kg/head/day.

The nutrient content of the input bedding and output manure from the HRHB (Table 5.3 & 5.4) showed that phosphorous was generally conserved within the HRHB since no gases that contain phosphorous were generated during the production process. Approximately 0.2 kg P/pig in summer and 0.32 kg P/pig in winter, which accounted for 19% and 24% of the total phosphorous in summer and winter respectively, were lost during growth in the high rise system (Figure 5.1, 5.2 & Table 5.3, 5.4). This indicates that some phosphorus was lost with liquids and solids that drained out of the building.

<table>
<thead>
<tr>
<th></th>
<th>Total (Metric tons)</th>
<th>Average (kg pig(^{-1}))</th>
<th>Rate (g pig(^{-1}) day(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Summer group</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>3.77±0.17</td>
<td>3.77±0.17</td>
<td>32.0±1.44</td>
</tr>
<tr>
<td>P</td>
<td>0.20±0.02</td>
<td>0.20±0.02</td>
<td>1.68±0.21</td>
</tr>
<tr>
<td>K</td>
<td>0.63±0.04</td>
<td>0.63±0.04</td>
<td>5.34±0.37</td>
</tr>
<tr>
<td><strong>Winter group</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>4.13±0.18</td>
<td>3.95±0.18</td>
<td>31.3±1.40</td>
</tr>
<tr>
<td>P</td>
<td>0.33±0.03</td>
<td>0.32±0.03</td>
<td>2.52±0.22</td>
</tr>
<tr>
<td>K</td>
<td>0.94±0.04</td>
<td>0.90±0.04</td>
<td>7.15±0.32</td>
</tr>
</tbody>
</table>

The error is standard error, calculated based on the assumption the samples are independent.

Table 5.4: Total mass, Nitrogen and Phosphorus losses from the HRHB
Figure 5.1: Phosphorous balance of HRHB for winter production cycle; A) total input of Phosphorous to the system; B) total output of Phosphorous from the building
Figure 5.2: Phosphorous balance of HRHB for summer production cycle; A) total input of Phosphorous to the system; B) total output of Phosphorous from the building
The release of potassium through gas emissions was also assumed to be negligible. However, the amount of potassium lost was different than phosphorous. More than 45% of the original potassium was lost during the production process (Figure 5.3 & 5.4). The potassium losses were 0.63 kg K/pig in summer and 0.90 kg K/pig in winter (Table 5.3 & 5.4). The greater losses of potassium may be due to the higher solubility of potassium in the drainage liquid as compared to phosphorous. (MWPS, 2000).

Considerable nitrogen loss also occurred from the HRHB during the production process (Table 5.3, 5.4 & Figure 5.5, 5.6). Less than 50% of the total nitrogen input remained in the animals and manure bed mixture at the end of the process. These nitrogen losses were equivalent to 3.77 kg N/pig in summer and 3.95 kg N/pig in the winter (Table 5.4). Both drainage of liquid manure and emission of ammonia, dinitrogen gas and NO\textsubscript{x} likely contributed to this considerable loss of nitrogen from the system. Of these, the volatile losses of nitrogen in the form of ammonia, NO\textsubscript{x} and nitrogen gas were believed to be the main contributors. The HRHB was built with a concrete floor with a drainage system to move the liquid that overflows from the storage area to a small pond that is close to the HRHB. In previous studies a negligible amount of liquid overflowed and left the building. However in these experiments sub optimal bed aeration was used resulting in incomplete drying of the bed. Unfortunately, the liquid leaving the building could not be quantified in this experiment so leachate losses were only estimated.
Figure 5.3: Potassium balance of HRHB for winter production cycle; A) total input of potassium to the system; B) total output of potassium from the building
Figure 5.4: Potassium balance of HRHB for summer production cycle; A) total input of potassium to the system; B) total output of potassium from the building.
Figure 5.5: Nitrogen balance of HRHB for winter production cycle; A) total input of nitrogen to the system; B) total output of nitrogen from the building
Figure 5.6: Nitrogen balance of HRHB for summer production cycle; A) total input of nitrogen to the system; B) total output of nitrogen from the building.
To estimate nitrogen loss through drainage, it was assumed that the concentration ratio of nitrogen and potassium in the leachate was constant; all leachate flowed into a storage tank in the building and then overflowed to a pond; and that the potassium losses were mainly from the drainage of liquid manure. Based on these assumptions and the measurement of liquid samples from the storage tank, the nitrogen/potassium ratio was obtained as 1:3. The nitrogen loss through drainage of liquid manure was calculated as 5.6% and 7.6% of total nitrogen loss in summer and in winter, respectively. This demonstrated that most nitrogen were lost through air. (Michel et al. 2001, Arogo et al., 2001)

The associated windrow composting processes were mainly completed at Fresh Air Farms and the Ohio Agricultural Research and Development Center (OARDC). Sawdust was used as amendment to reduce moisture content to 61% and increase carbon/nitrogen ratio to approximately 28:1. Temperature and oxygen content in the compost windrow were monitored. The mean compost temperatures were over 55°C within 2 days of windrow formation and maintained this level for about 80 days, thereby exceeding US-EPA pathogen reduction criteria (Figure 5.7). The oxygen content at 1.5 feet below the surface was lower than 5% within 40 days (Figure 5.8). After than, it gradually increased, which indicated that the compost was becoming stabilized.
Figure 5.7: Temperature during composting of HRHB manure/bedding at OARDC composting site. The error was the standard deviation of measurement (n=3-12)
Figure 5.8: Oxygen content at 1.5 feet below the surface of HRHB hog manure/bedding windrow compost at OARDC composting site. The error was the standard deviation of measurement (n=3-6)
# Nutrient losses

<table>
<thead>
<tr>
<th></th>
<th>Sawdust (Amendment)</th>
<th>Manure from HRHB</th>
<th>Initial compost</th>
<th>Final compost</th>
<th>Nutrient losses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total wet weight (kg)</td>
<td>3740</td>
<td>17677</td>
<td>21417</td>
<td>7144</td>
<td>14273</td>
</tr>
<tr>
<td>Solids</td>
<td>87.2%</td>
<td>30.1%</td>
<td>39%</td>
<td>64.8%</td>
<td></td>
</tr>
<tr>
<td>Dry weight (kg)</td>
<td>3261</td>
<td>5321</td>
<td>8395</td>
<td>4629</td>
<td>3766</td>
</tr>
<tr>
<td>Total N (kg)</td>
<td>7.83±0.65</td>
<td>167.6±2.1</td>
<td>164.55±0.8</td>
<td>139.67±2.13</td>
<td>24.88±2.29</td>
</tr>
<tr>
<td>Total P (kg)</td>
<td>0.66±0.10</td>
<td>67.6±3.2</td>
<td>*68.22±3.2</td>
<td>63.42±2.35</td>
<td>4.81±3.97</td>
</tr>
<tr>
<td>Total K (kg)</td>
<td>3.79±0.38</td>
<td>109.1±4.8</td>
<td>126.77±0.3</td>
<td>116.66±0.86</td>
<td>10.11±0.93</td>
</tr>
</tbody>
</table>

* calculated value from the mixture of sawdust and manure. The error is the standard error, calculated based the assumption that the samples are independent.

Table 5.5: Total mass, N, K and P losses from the composting process (at OARDC composting site for winter group).
The mass balance study of composting process at OARDC composting site showed most N, K, P were conserved in the compost product (Table 5.5). 45% dry matter, 15% nitrogen, 7% phosphorus, and 8% potassium from the manure/amendment mixture removed from the HRH was lost during the 100 day composting process.

Fresh Air Farm used different materials including straw and yard trimmings as composting amendment to balance moisture content and C:N ratio. Straw that had higher moisture and nitrogen content than sawdust was added to the manure/bedding materials from the summer group. The moisture content was measured as 68% and C:N ratio was 28:1. The mass balance study showed that most N, K, P were conserved in the compost product (Table 5.6). 8.9% dry matter, 10% nitrogen, 1% phosphorus, and 4% potassium from the manure/amendment mixture removed from the HRH were lost through gas volatilization, run off and leaching. The whole process was completed on a bare ground, which is different from the concrete surface at the OARDC composting site. This may be a factor that resulted in the higher standard deviation in measured values at Fresh Air Farms as compared to those from OARDC composting group (Table 5.5-5.7).

Yard trimmings were added to the manure/bedding materials from the winter group. Compared with straw and sawdust, yard trimmings have a low cost. The moisture and nitrogen content of yard trimming are lower than straw but higher than sawdust. With the mixture of yard trimmings, the initial compost had a moisture content of 61% and C:N ratio of 20:1. More nitrogen (25%) was lost during composting of this material than
<table>
<thead>
<tr>
<th></th>
<th>Straw (Amendment)</th>
<th>Manure from HRHB</th>
<th>Initial compost</th>
<th>Final compost (kg)</th>
<th>Nutrient losses (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet Weight (kg)</td>
<td>26263</td>
<td>109771</td>
<td>136035</td>
<td>99004</td>
<td>37031</td>
</tr>
<tr>
<td>Solids</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dry weight (kg)</td>
<td>12895</td>
<td>27553</td>
<td>44157</td>
<td>40235</td>
<td>3922</td>
</tr>
<tr>
<td>Total N (kg)</td>
<td>181.8±12.9</td>
<td>823.8±16.5</td>
<td>1002.4±13.2</td>
<td>905.3±50.9</td>
<td>97.1±52.6</td>
</tr>
<tr>
<td>Total P (kg)</td>
<td>35.4±1.3</td>
<td>372.1±12.6</td>
<td>485.7±6.5</td>
<td>482.8±34.0</td>
<td>2.9±17.3</td>
</tr>
<tr>
<td>Total K (kg)</td>
<td>273.3±19.2</td>
<td>663.4±36.4</td>
<td>1010.8±14.0</td>
<td>972.6±70.0</td>
<td>38.2±35.7</td>
</tr>
</tbody>
</table>

The error is the standard error, calculated based on the assumption that the samples are independent.

Table 5.6: Total mass, N, K and P losses from the composting process (at Fresh Air Farm composting site for summer group).
<table>
<thead>
<tr>
<th></th>
<th>Yard trimming, ground wood, (Amendment)</th>
<th>Manure from HRHB</th>
<th>Initial compost</th>
<th>Final compost</th>
<th>Nutrient losses</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(kg)</td>
</tr>
<tr>
<td>Wet Weight (kg)</td>
<td>66357</td>
<td>116323</td>
<td>183173</td>
<td>106188</td>
<td>76985</td>
</tr>
<tr>
<td>Solids %</td>
<td>57.7%</td>
<td>29.7%</td>
<td>40.5%</td>
<td>55.9%</td>
<td></td>
</tr>
<tr>
<td>Dry weight (kg)</td>
<td>38268</td>
<td>34548</td>
<td>74112</td>
<td>59306</td>
<td>14806</td>
</tr>
<tr>
<td>Total N (kg)</td>
<td>451.6±26.8</td>
<td>1071.0±13.8</td>
<td>1385.9±42.2</td>
<td>1043.8±48.0</td>
<td>342.1±64.0</td>
</tr>
<tr>
<td>Total P (kg)</td>
<td>47.1±3.5</td>
<td>438.8±21.8</td>
<td>560.0±31.1</td>
<td>557.5±41.4</td>
<td>2.5±51.8</td>
</tr>
<tr>
<td>Total K (kg)</td>
<td>141.7±0.9</td>
<td>727.7±32.3</td>
<td>837.5±51.8</td>
<td>827.1±54.3</td>
<td>10.4±75.0</td>
</tr>
</tbody>
</table>

The error is the standard error, calculated based the assumption that the samples are independent.

Table 5.7: Total mass, N, K and P losses from the composting process (at Fresh Air Farm composting site for winter group).
the other two composts. The potassium and phosphorus losses were negligible. The higher nitrogen loss may be due to the lower initial C:N ratio of the compost (Tiquia, 2000).

Composting of the hog manures removed from the HRHB offered several benefits (Rynk, 1992). Further moisture reduction improved the economics of manure transportation and allowed for a wider area of distribution. Stabilized compost did not emit odors or attract flies. It was free of pathogens and provided a long term, storable source of nutrients for crops and other plant production markets. Composts also have been shown to suppress diseases of plants and thus reduce pesticide use, commanding a value in excess of their nutrient content (Hoitink et al., 1997).

Overall, the average nitrogen, phosphorous and potassium losses from the HRH building during both summer and winter periods were 3.86kg/head, 0.25 kg/head and 0.76 kg/head, representing 52, 21, 47% of the initial respectively due to the volatilization (N) and liquid drainage (N, P, K). After manure was removed from the building and composted, most N, P and K were conserved in the final compost product. Only 17% nitrogen, 3% phosphorus, and 4% potassium from the initial manure/amendment mixture was lost throughout a 100 days composting process. In total, about 57, 22, and 48% of the total N, P, K inputs (including the part from the amendment for composting process) were lost from the whole HRHB system during hog production and composting.

These losses are comparable to the losses from a conventional hog farm. A mass balance analysis showed 50% loss of P in a conventional liquid based hog manure management system, that was accumulated in the liquid storage lagoon (Nelson and
Mikkelsen, 2001), the HRHB system had less than half the phosphorous accumulation (22% of total P input) in liquids. In another words, HRHB could significantly reduce the potential of phosphorous pollutions to surface and ground water.

The nitrogen loss of 3.86 kg N/pig for pigs growing between 20 kg and 120 kg from the High Rise Hog building was comparable to the 3 kg N/pig for pigs growing between 25 kg and 105 kg in a conventional deep litter system (Thelosen et al., 1993) and 3.9 kg N/pig for pigs between 23 kg and 117 kg from hoop structure system (Garrison et al., 2001). In HRHB system, about 34 to 36% total nitrogen input was left in animals. This compares to 33-35% left in animals, 17 to 19% in the feces and 45 to 50% in the urine reported by Dourmad et al (1999).

To reduce nutrient losses and reduce their environmental impact of the HRHB system, additional operational strategies may be required. Although phosphorous loss and accumulation in the farm pond was more than 50% less than that in a lagoon system, larger drainage and leachate storage tanks and regular removal of liquid manure from them could additionally reduce phosphorous discharge to environment and provide possible fertilizers to crops (with potassium concentration of 5.8 g K/l and nitrogen concentration of 2.1 g N/l). The HRHB used aeration and porous bedding to absorb moisture and dry the manure. The amount of liquid drainage was calculated as 1.1 l/pig/day based on potassium loss and concentration in the drainage storage tank. For a 1000 head HRHB, a 4 x 5 x 6 m storage tank could satisfy the requirement that the liquid manure must be removed once per production cycle.
Nitrogen loss was significant from the HRHB, which was mainly from the volatile losses of nitrogen in the form of ammonia, NO\textsubscript{x} and nitrogen gas. Control of gas volatilization and recovery of gas emissions could reduce these nitrogen losses. Based on a previous study, an ammonia scrubber system and spraying acid onto manure might reduce nitrogen losses from the HRHB (Zhao et al., 2001; Hattey et al., 2001)

5.2 Air Quality- Ammonia Concentration

Ammonia concentrations in the HRHB were measured regularly during summer and winter production cycles. The results showed that in summer ammonia concentration did not exceed 2.5 ppm in the pig space (Figure 5.9). However, ammonia concentrations in the lower level of the building were much higher than that in the upper level. The average ammonia levels at two elevations of just above and 1.5 feet above the manure bedding were in a range of 18 to 30 ppm and 8 to 13 ppm, respectively (Figure 5.10).

In winter, the average ammonia concentration in the upper level of the building was as high as 16 ppm (Figure 5.11). The highest measured ammonia concentration in the pig space was nearly 30 ppm on Dec 4\textsuperscript{th} when the outdoor temperature was below -4°C (25 F). In the lower level of the building, average ammonia concentrations on two elevations of just and 1.5 feet above the manure bedding were in a range of 23 to 51 ppm and 22 to 44 ppm, respectively (Figure 5.12). During the most growth period in winter, ammonia concentrations above the manure storage area were over the threshold limit value (TLVs) of 25 ppm. Suitable protective gear should be worn for operators when entering the lower level of the building. With the growth of pigs and manure
Figure 5.9: Average ammonia concentrations (n = 6) at 8 positions and two elevations within a HRH building in summer. (A) at the elevation of 4 feet above the slatted floor; (B) at an elevation of 6 feet above the slatted floor. Error bars are standard deviations.
Figure 5.10: Average ammonia concentrations at two elevations of just and 1.5 feet above the manure bedding material within the lower level of HRHB measured on different dates in winter. Hogs were grown from May 28 to Sept 27.
Figure 5.11: Average ammonia concentrations in winter (n =7) at 8 positions and two elevations within a HRH building. Locations are shown in fig. 2. (A) at an elevation of 4 feet above the slatted floor; (B) at an elevation of 6 feet above the slatted floor. Error bars are standard deviations.
Figure 5.12 Average ammonia concentrations at two elevations of just above and 1.5 feet above the manure bedding material within the lower level of HRHB measured on different dates in winter. Hogs were grown from Oct 15 to Feb 19
accumulation, ammonia concentrations on the surface of manure bedding likely increased (Figure 5.12). Low ventilation rate resulted in high ammonia concentration in the building.

A one-way ANOVA model was used to test the hypotheses that the outdoor temperature did not affect room ammonia concentration and that indoor/outdoor temperature difference did not affect room ammonia concentration, respectively. Both p-values were less than 0.001. The ammonia concentration across the pig space did not correlate significantly with the animal growth (Figure 5.13) in winter. However, it was significantly correlated to the outdoor temperature and indoor/outdoor temperature difference (Figure 5.14 & 5.15). Higher ammonia concentrations were found under lower outdoor temperatures and higher indoor/outdoor temperature differences. During these periods less ventilation was used to reduce heat loss from the building.

Since the data were collected independently, two linear regression models were developed to show the relationship between ammonia concentration in the pig space and outdoor temperature or indoor/outdoor temperature difference.

\[ C_{\text{ammonia}} = 0.044 \times T_{\text{outdoor}}^2 - 1.162 \times T_{\text{outdoor}} + 18.974 \]

\[ C_{\text{ammonia}} = 0.042 \times \Delta Temp^2 - 0.329 \times \Delta Temp + 11.175; \]

Where

\( C_{\text{Ammonia}} \) = ammonia concentration (ppm),

\( T_{\text{outdoor}} \) = Outdoor temperature (°C).

\( \Delta Temp \) = indoor/outdoor temperature difference in winter (°C).
Figure 5.13: Average ammonia concentrations at two elevations of 4 feet and 6 feet above the second floor within a HRH building measured on different dates in winter. Hogs were grown from Oct 15 to Feb 19.
Regression Equation: \[ C_{ammonia} = 0.044 \times T_{outdoor}^2 - 1.162 \times T_{outdoor} + 18.974 \]

\( C_{Ammonia} \) = ammonia concentration (ppm),
\( T_{outdoor} \) = Outdoor temperature (°C).

Figure 5.14: Ammonia concentrations in the pig space measured under difference outdoor temperature around noon in winter.
Regression Equation: \[ C_{ammonia} = 0.042 \times \Delta Temp^2 - 0.329 \times \Delta Temp + 11.175; \]

\(C_{Ammonia}\) = ammonia concentration (ppm),
\(\Delta Temp\) = indoor/outdoor temperature difference in winter (°C).

Figure 5.15: Ammonia concentrations in the pig space measured with various indoor/outdoor temperature differences around noon in winter.
Using these regression models, a critical outdoor temperature of -5°C and indoor/outdoor temperature difference of 23°C were predicted over which ammonia concentration in the pig space could exceed the threshold limit value (TLVs) of 25 ppm.

To address this issue, heaters could be used to heat the inlet air and reduce the indoor/outdoor temperature difference. This could increase the minimum ventilation rate required to maintain room temperatures in the HRHB. The increased ventilation condition would improve air quality for animals and workers in the upper level of the building. However, during minimum ventilation periods, the ammonia level in the pig space is predicted to be higher than the exposure limit of 7 ppm suggested by Donham et al (1989). The adverse effect on hogs and workers’ health may not be avoidable in winter based on this finding.

The measured ammonia concentrations in the HRH facility were comparable to conventional swine confinement units. Groot Koerkamp et al. (1998) reported that the ammonia concentrations in different houses for finishing swine in North Europe were between 5 and 18 ppm with a maximum ammonia concentration range from 21.7 to 58 ppm. The houses with slats generally had a higher value than those with litter. In this study, the measured mean ammonia concentrations in the pig area of HRHB were 8.5 ppm (1 ppm in summer and 16 ppm in winter). The maximum ammonia concentration was never greater than 30 ppm in the pig space.

Ammonia concentration was also intermittently monitored in the exhaust air. The results showed a large variability from one sampling date or fan location to another in winter (Figure 5.16 & 5.17). The ammonia concentrations in the exhaust air ranged from

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1 ppm to 18 ppm in summer and from 5 ppm to 35 ppm in winter. This large variability could be due to factors such as fan location, aeration rate through the manure/bedding material, indoor/outdoor temperatures, animal activities, ammonia concentrations on the surface of the manure, and air pressure.

Total ammonia emission rates from the HRHB were estimated based on the ammonia concentrations and airflow rates measured across the exhaust fan (Figure 5.18 & 5.19). In winter, ammonia was released from the building at a rate of $12.4 \pm 4.5$ g NH$_3$/pig/day, which was about 33% of the total nitrogen loss from the HRHB. In summer, under the higher ventilation conditions, ammonia emission rate was estimated to be $14.4 \pm 5.1$ g NH$_3$/pig/day, which was close to that in winter. Based on this analysis, the nitrogen loss through ammonia emission is estimated to be approximately 37% of the total nitrogen lost from the HRHB in summer. The rest of the nitrogen loss was probably due to losses of other nitrogenous gases such as N$_2$, N$_2$O and NO$_x$. Therefore, using a nitrogen balance approach may overestimate ammonia emission rates and may not be appropriate for the HRHB system or similar systems where multiple gaseous nitrogen species can be produced.
Figure 5.16: Ammonia concentrations measured at the selected exhaust fans in winter. Hogs were grown from Oct 15 to Feb 19. NW-S represented the small fan located at the northwest corner of building; NC-S represented the small fan located at the north center of building; and SW-S represented the small fan located at the Southwest corner of building.
Figure 5.17: Ammonia concentrations measured at the selected exhaust fans in summer. Hogs were grown from May 28 to Sept. 27. NW-L1 represented the first large fan located at the northwest corner of building; NW-L2 represented the second large fan located at the northwest corner of building; and SW-L1 represented the first large fan located at the southwest corner of building.
Figure 5.18: Ammonia emission rate from the HRHB in winter calculated based on ammonia concentration in the exhaust air and airflow rate through the exhaust fans.
Figure 5.19: Ammonia emission rate from the HRHB in summer calculated based on ammonia concentration in the exhaust air and airflow rate through the exhaust fans.
5.3 Two-dimensional Model of airflow and ammonia distribution in a HRHB

To further understand airflow and ammonia distributions in the HRHB, computational fluid dynamic models were developed. The first models developed were 2-dimensional laminar and turbulent flow models using measurements made in winter as the initial and boundary conditions. Two models were used since both turbulent and laminar flows occur in the building. Ammonia concentrations in the pig space were measured at several locations in an empty HRHB to validate the models (Figure 4.11 & 4.12).

Results show that for both models, the simulated main airflow pattern was outward from the ceiling inlets and downward within the pig space (Figure 5.20 & 5.21). In the lower level, the pattern was upward from the drying bed and toward the exhaust. Both laminar and turbulent flow models showed that there was some air flowing from the lower to the upper levels (Figure 5.22). A well-defined vortex is evident close to the walkway upstairs. Along the wall, air was projected to flow rapidly down and through the slotted floor. Because the slotted floor had a porosity of 0.14, the pressure drop across the floor was negligible under the minimum ventilation condition.

A slight difference of the flow patterns between the laminar and turbulent flow models was that a vortex was evident close to the exhaust fan in the laminar flow model as compared to no vortex in the turbulent flow model. The laminar flow model predicted that a considerable amount of air was transported from pit area to the pig space. However, much less air was transported from the lower to the upper level in the turbulent flow model (Figures 5.20 & 5.21). Both models showed that the airflow velocity at the
ceiling baffle exit was about 2.8 m/s which was within the range of 2.68 to 3.58 m/s previously measured (Stowell, 1999).

The laminar flow models predicted that the concentration of ammonia near the walkway would be 23 ppm in the upper level and approximately 60 ppm in the lower level (Figure 5.23). The former value is higher than the range of 5-19 ppm previously measured in the upper level during winter (Stowell, 1999). The laminar flow model also predicted ammonia levels as high as 40 ppm in the pig area (Figure 5.23).

The turbulent flow model predicted that the concentration of ammonia near the walkway would be 17 ppm in the upper level and 46 ppm in the lower level. The turbulent flow model predicted ammonia concentrations were less than 25 ppm in the pig space (Figure 5.24). These values more closely approximate the levels measured previously (Stowell, 1999) at these locations.

The ammonia concentrations predicted by both laminar and turbulent flow models were compared to the measured values (Figure 5.25). The turbulent flow model more closely matched measured ammonia values at the three locations. However, both showed some deviations in predicted ammonia concentrations from the measured values. This may have been due to the limitations of imposing a 2-dimensional model on a 3-D geometry.

In summary, the 2-dimensional CFD models allowed rapid simulation of airflow and gas concentrations in the HRHB. Compared with airflow velocity and ammonia concentrations measured previously, both laminar and turbulent flow models resulted in predicted concentration gradients throughout the building near measured values.
Figure 5.20: Air velocity vector distribution in a High-rise hog building as predicted using a CFD laminar flow model. Arrow size and length are proportional to air velocity. Some arrows are outside the Figure boundary. Model geometry is as shown in Fig. 4.
Figure 5.21: Air velocity vector distribution in a High-rise hog building as predicted using a CFD turbulent flow model. Arrow size and length are proportional to air velocity. Some arrows are outside the Figure boundary.
Figure 5.22: Y-component of air velocity in a High-rise hog building as predicted by: A) a laminar flow CFD model, B) a turbulent flow model. Contour lines represent zero velocity in the y-direction. Right side represents building center, left side is the building sidewall.
Figure 5.23: Ammonia concentration contours for a High-rise Hog building as predicted using a laminar flow CFD model under low fan (winter) operation.
Figure 5.24: Ammonia concentration contours for a High-rise Hog building as predicted using a turbulent flow CFD model under low fan (winter) operation.
Figure 5.25: Comparison of average ammonia concentrations (n=3) and predictions from both laminar and turbulent models at three 2D locations within the building (see Figure 4.11 & 4.12). Error bars are standard deviations.
However, the turbulent flow model better predicted measured ammonia concentration values than the laminar flow model. Both models showed deviations of predicted ammonia concentrations from the measured values.

5.4 Three-dimensional isothermal model of an empty HRHB

To improve the predictive ability of the 2-D models, a three-Dimensional isothermal CFD model of airflow field and ammonia concentration distribution in an empty HRHB was developed and validated. Compared to the 2-dimensional model, the 3-D model more accurately represented building geometry and operational processes such as exhaust fan placement and airflow distribution across the horizontal area of the animal space. The output of the model provided more details than the 2-D models about airflow velocities, pressures, turbulences and ammonia concentrations throughout the pig space. Since it was shown in 2-D models that the turbulent flow model better predicted measured ammonia concentration values than the laminar flow model, only turbulent flow model was used in the 3-D simulation.

5.4.1 Airflow pattern in an empty HRHB in summer and winter conditions

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 5.26). Little gas flowed back to the upper level and the air moved in a spiral pattern toward the exhaust fan. In the lower level, the pattern was upward from the drying bed and toward the exhaust fan. No air from Inlet 2 entered the upper levels (Figure 5.27).
Figure 5.26: The predicted airflow pathline from the ceiling inlet for summer condition in a HRHB.
Figure 5.27: The predicted airflow pathline from the inlet 2 for summer condition in a HRHB.
In winter, airflows were somewhat different than in summer due to lower ventilation rates. The models simulated airflow pathlines showed that two flow patterns existed in the HRHB at the same time (Figure 5.28). The simulated domain was divided into two parts to illustrate this phenomenon, one far away from the exhaust fan (Section A, Figure 5.28) and the other close to the exhaust fan (Section B, Figure 5.28). 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 5.27). A large vortex was formed across the slatted floor. Some air was predicted to recycle to the upper level (Figure 5.28). 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 (Figure 5.29). 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 (Figure 5.28). Little gas flowed back to the upper level. In the lower level, air flowed upward through drying bed and toward the exhaust. Very little air from Inlet 2 entered the upper levels (Figure 5.29). Most of the air coming from section A flowed toward the exhaust in a spiral pattern.

5.4.2 Ammonia Concentration in Summer and Winter conditions

In summer, the maximum ammonia concentration on the slatted floor in the pig space was predicted to be below 5 ppm (Figure 5.30). The ammonia distribution across the pig space was even (difference is less than 1.5 ppm); some locations close to the fan and center of the pen had slight higher ammonia concentration (Figure 5.30). The model
Figure 5.28 The predicted airflow pathlines from the ceiling inlet for winter conditions in a HRHB. The simulated space is divided into two parts, sections A and B, for the convenience of description.
Figure 5.29: The predicted airflow pathlines from the inlet 2 for winter conditions in a HRHB. The simulated space is divided into two parts, sections A and B, for the convenience of description.
Figure 5.30 Concentration contour of ammonia for summer condition in a HRHB. The plane about 4 feet high from the slatted floor in the building is selected to show the ammonia distribution throughout the airspace closest to the pigs.
Figure 5.31: Concentration contour of ammonia for winter condition in a HRHB. The plane about 4 feet high from the slatted floor in the building is selected to show the ammonia distribution throughout the airspace closest to the pigs.
showed the ammonia concentration was from 0.2 to 1.3 ppm at the height of 1.2 m (4 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).

In winter, the maximum ammonia concentration in the pig space was predicted to be less than 25 ppm (2 feet above the second floor). Near the walkway the ammonia concentration was around 11 ppm (1 meter high from the walkway surface). The highest ammonia concentration was found in the center of the pens. The pens that were far away from the exhaust fan exhibited higher ammonia concentration. At the height of 1.2 m (4 feet) in the pig area, the ammonia concentrations were from 9 to 17 ppm (Figure 5.31).

5.4.3 Validation of the 3-D CFD model

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 mainly within 20% of the averaged ammonia measurements at specific locations in both summer and winter (Figure 5.32 & 5.33) except those close to the fan. Both the 3-D 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 greater the ammonia concentration was likely to be. On the other hand, the ammonia distribution in the pig area was shown to be relatively evenly distributed in summer. The range of ammonia concentrations at locations of 1.2 m (4 feet) or 1.8 m (6 feet) above the second floor were from 0.3 to 1 ppm.
Figure 5.32: Comparison of average ammonia concentrations (n =2 or 3) and predictions from the 3-D CFD model at 8 positions of two elevations within the building (see fig. 6) in summer. Error bars are standard deviations. Measurement location 1-4 represents the point at the position 1 (Fig. 6) and the elevation of 4 feet high from the slatted floor.
Figure 5.33: Comparison of average ammonia concentrations (n = 2 or 3) and predictions from the 3-D CFD model at 8 positions of two elevations within the building (see fig. 6) in winter. Error bars are standard deviations. Measurement location 1-4 represents the point at the position 1 (Fig. 6) and the elevation of 4 feet high from the slatted floor.
The accuracy of the model were validated by experimental measurements of ammonia concentrations. Compared to the previously developed 2-dimensional model, the 3-D model clearly showed the effect of the location of exhaust fans on ammonia concentration and airflow pattern in the hog area. In winter, ammonia distribution in the pig space was found to be strongly related to the distance from the fan outlet. Furthermore, the 3-D airflow pictures showed that the airflow might have completely different patterns in various sections at different distances from the fan outlet. These findings demonstrated the superiority of the 3-D model to the 2-D model. These outputs could help designers to further study the placement of exhaust fans and to achieve an optimum air quality in the pig space.

5.5 Three-dimensional non-isothermal model of a hog occupied HRHB

Although some previous studies have shown that body shapes, orientations, skin wetness, and movements of a large group of lying or standing animals does not significantly affect indoor airflow pattern (Wu and Gebremedhim, 2000; Gebremedhim and Wu, 2000; Svidt et al., 1998; Bjerg et al., 1999), animal bodies in the HRHB may have large effect on air movement by changing airflow space geometry and blocking the slatted floor. These might result in changes in the pressure drop through the slat, different airflow routes through the animal space and heterogeneous ammonia distributions in the pig area. Furthermore, heat transfer from animal bodies to the environment could contribute to air movement and ammonia distribution in the building, especially when the indoor/outdoor temperature difference was large and the outdoor temperature was very
Figure 5.34 Predicted airflow pathlines starting from inlet 2 for summer condition in an occupied HRHB
Figure 5.35 Predicted airflow pathlines starting from ceiling inlet for summer condition in an occupied HRHB
low. Previous studies have shown that air convection due to buoyancy effects can be significant under the low ventilation conditions (Zhang et al. 1999).

5.5.1 Airflow pattern in an occupied HRHB in summer and winter conditions using the 3D model

To simulate animals in the HRHB, it was assumed that 1) the animal’s shape did not significantly affect the overall airflow pattern in the building; 2) the average animals size was 30 x 45 x 90 cm; 3) The animal surface temperature was 37°C. Results showed that the predicted airflow pathlines in an animal occupied HRHB in summer exhibited a similar pattern to that observed in the empty HRHB model. The main airflow pattern was outward from the ceiling inlets and downward within the pig space (Figure 5.35), Little gas flowed back to the upper level; In the lower level, the pattern was upward from the drying bed and toward the exhaust fan. No air from Inlet 2 entered the upper levels (Figure 5.34). A slight difference was that most air moved in a spiral pattern in the upper level toward the exhaust fan and well mixed with room air because of the block of animal body on the slatted floor.

In winter, however, the airflow pattern was less similar to that in the empty HRHB particularly when the outdoor temperature was 0°C (32 F). The predicted airflow pathlines showed cold air entered from the ceiling inlet, went outward and downward to the outlet reducing ventilation in the pig area (Figure 5.36). In the lower story of the building, some air blown through the manure mixture went upward and entered the upper story, which could potentially carry ammonia into the pig space (Figure 5.37). Most of
the air flowed toward the exhaust in a spiral pattern. However, with a few solid blocks on
the second floor and a strong temperature gradient from the center ceiling inlet to
periphery (Figure 5.38), the airflow pattern was different from that under isothermal
conditions. Airflow vortexes were formed above the pigs; with cold air flowing away
from ceiling inlet, dropping quickly downward from the ceiling to animal space, passing
over the animals and heated, going upward from the hog surfaces and then being mixed
with the cold air leaving ceiling inlet (Figure 5.36 5.37 & 5.39). The air was well mixed
above animal space. The room temperature over the entire animal space at 1.2 m (4 feet)
and 1.8 m (6 feet) high above the second floor was almost constantly around 18°C
(Figure 5.40). This level was near the optimal temperature for animal growth. There was
more than 10 degrees temperature difference between the ceiling and room area (6 feet
above the second floor). Cold air leaving ceiling inlet did not travel as far as that that
under isothermal conditions (Figure 5.39 & 5.21). These airflow patterns indicated that
animal bodies and thermal buoyancy effects were important factors for airflow movement
above the pig area during the minimum ventilation period in winter.
Figure 5.36 Predicted airflow pathlines starting from ceiling inlet for winter condition in an occupied HRHB
Figure 5.37 Predicted airflow pathlines starting from surface of the manure bedding for winter condition in an occupied HRHB.
Figure 5.38: Temperature contour on the ceiling surface for winter condition in a occupied HRHB. Outdoor temperature was 0°C or slight below.
Figure 5.39: Air velocity vector distribution on a plane across the fan outlet for winter condition in an occupied High-Rise™ hog building. Ceiling inlet size was 6 mm. Arrow size and length are proportional to air velocity. Some arrows are outside the Figure boundary.
Figure 5.40: Temperature contour for winter condition in a occupied HRHB. Outdoor temperature was 0°C or slight below. The plane is 2 feet above the slatted floor in the building.
5.5.2 Ammonia distribution in a HRHB in summer and winter conditions using the 3D model

Since the aeration fans using to dry manure bedding were turned on for 10 minutes, and off for 50 minutes periodically, an intermittent aeration model was used to predict ammonia concentrations in the building, which included two separate CFD models; one with continuous aeration and the other without aerations to dry the manure bedding. Two time-weight numbers of 1/6 and 5/6 were used to average the output of two models and generate estimates of the average ammonia concentrations in the building.

In summer, the time-averaged CFD model predicted that the average ammonia concentrations were less than 2 ppm at two elevations of 4 and 6 feet above the slatted floor when the outdoor temperature was from 27 to 32°C (Figure 5.41, 5.42 & 5.43). The model that simulated continuous aeration process using to dry the manure predicted slight higher ammonia concentration (<1.5 ppm) than that simulating no aeration for manure bedding (Figure 5.42 & 5.43).

In winter, the highest ammonia concentration of 30 ppm were found in the center of the pens at 2 feet above the second floor when the aeration fans were turned on and the outdoor temperature was the median measured temperature of 0°C (Figure 5.44). Near the walkway the ammonia concentration was only around 15 ppm (1 meter high from the walkway surface), which falls in a range of 2-19 ppm in winter measured by Stowell et al. (1999). Higher ammonia concentrations in the pig space were found under lower outdoor temperature with the same minimum ventilation rate (Figure 5.44-5.49). When
Figure 5.41: predicted ammonia concentrations at three elevations in an occupied HRHB; 1.5 feet above the manure area, 4 feet above the slatted floor in the pig area, and 6 feet above the slatted floor in the pig area. “Predicted w/ aeration” represents the data from the model using air velocity inlet for inlet 2. “Predicted no aeration” represents the data from the model that uses wall boundary condition to simulate the situation with no aeration through the bedding. “Predicted intermittent aeration” represents a time-averaged ammonia concentration for intermittent aeration model. The measured ammonia concentration just above the manure area of 24.7 ppm was used as a boundary condition in the CFD models.
Figure 5.42 Concentration contour of ammonia (ppm) for summer condition in an occupied HRHB. The aeration fans were turned on to dry the manure. The plane about 2 feet high from the slatted floor in the building was selected to show the ammonia distribution throughout the airspace closest to the pigs.
Figure 5.43 Concentration contour of ammonia (ppm) for summer condition in an occupied HRHB. The aeration fans were turned off. The plane about 2 feet high from the slatted floor in the building was selected to show the ammonia distribution throughout the airspace closest to the pigs.
Figure 5.44: Concentration contour of ammonia (ppm) for winter condition in a HRHB. The aeration fans were turned on to
dry the manure. The outdoor temperature was 0°C. The plane about 2 feet high from the slatted floor in the building is selected
to show the ammonia distribution throughout the airspace near the pigs
Figure 5.45: Concentration contour of ammonia (ppm) for winter condition in a HRHB. The aeration fans were turned off. The outdoor temperature was 0°C. The plane about 2 feet high from the slatted floor in the building is selected to show the ammonia distribution throughout the airspace near the pigs.
Figure 5.46: Concentration contour of ammonia (ppm) for winter condition in a HRHB. The aeration fans were turned on to dry the manure. The outdoor temperature was -5°C. The plane about 2 feet high from the slatted floor in the building is selected to show the ammonia distribution throughout the airspace near the pigs.
Figure 5.47: Concentration contour of ammonia (ppm) for winter condition in a HRHB. The aeration fans were turned off. The outdoor temperature was -5°C. The plane about 2 feet high from the slatted floor in the building is selected to show the ammonia distribution throughout the airspace near the pigs.
Figure 5.48: Concentration contour of ammonia (ppm) for winter condition in a HRHB. The aeration fans were turned on to dry the manure. The outdoor temperature was 5°C. The plane about 2 feet high from the slatted floor in the building is selected to show the ammonia distribution throughout the airspace near the pigs.
Figure 5.49: Concentration contour of ammonia (ppm) for winter condition in a HRHB. The aeration fans were turned off. The outdoor temperature was -5°C. The plane about 2 feet high from the slatted floor in the building is selected to show the ammonia distribution throughout the airspace near the pigs.
the aeration fans were turned off, the CFD model predicted lower ammonia concentrations in the pig space than that with fans turned on (Figure 5.44-5.49). The pens that were furthest from the exhaust fan exhibited the highest ammonia concentrations. The time-averaged CFD model predicted that the average ammonia concentrations were less than 28 ppm at two elevations of 4 and 6 feet above the slatted floor when the outdoor temperature was around 0°C (32 F) (Figure 5.44 & 5.45).

5.5.3 Performance of ventilation system

The performance of the ventilation system of the HRHB was evaluated by investigating airflow rate through the exhaust fan and the ammonia concentrations across the pig area. The CFD models predicted the airflow rate through the exhaust fan was 4.8 m³/s in summer and 1.08 m³/s in winter. The measured airflow rates were from 3.6 m³/s to 5.4 m³/s through the large exhaust fans in summer and from 0.70 to 1.35 m³/s through the small fans in winter. The large swing of measured value could be due to several factors such as wind directions, wind speeds, fan performance, and/or air pressures. The ventilation rate for each animal space is 0.043 to 0.065 m³/s/head in summer and 0.004 to 0.008 m³/s/head in winter. The reduced airflow rate in winter was used to conserve room temperature, which could also result in poorer air quality in the building.

Both CFD models and measurements showed that the ventilation system of the HRHB provided good air quality environment for animals and workers in summer conditions with relatively low (<5 ppm) concentrations of ammonia. In winter however, the CFD models predicted that some air blown through the manure bed could flow up into the pig space, which could lead to ammonia concentrations as high as 30 ppm in the upper
level of the building. This might be caused by the aeration used to dry manure mix, re-
circulation of the airflow in the building or both. Based on the output of the model for
winter conditions, optimization of the ventilation system may be needed to improve airflow
and reduce ammonia concentrations in the pig area to maximize animal health during
periods of minimal ventilation.

5.5.4 Validation of the CFD model

The 3D model predicted ammonia concentrations and temperatures in one section
of the building (Figure 4.2) while the validation measurements were made in similar
sections through the building. The model-predicted values at the measurement locations out
of the simulated area had to been estimated based on the assumption that each airflow
space in the building was symmetric with the closest exhaust fan plane and central
walkway plane.

The predicted ammonia concentration in summer condition was a time-averaged
value from 4 cases with different outdoor temperature and aeration strategies (Table 4-10).
The predicted values closely matched the measurements made under similar conditions.
(Figure 5.50). A two-way ANOVA analysis showed that no statistical difference between
model-predicted ammonia concentrations and measured values were found. The $p$-value
was calculated as 0.67 which was much greater than the significance level of 0.05. The
ammonia distribution in the pig space was not associated to the sampling locations in
summer. The $p$-value was larger than 0.9.
Figure 5.50. Comparison of average ammonia concentrations (n = 3) to predictions from the CFD models at 8 positions and two elevations within the building (see fig. 2) in summer, (A) at the elevation of 4 feet above the slatted floor; (B) at an elevation of 6 feet above the slatted floor. Error bars are standard deviations.
Figure 5.51: Comparison of average ammonia concentrations (n =4) to predictions (n=3) from the CFD models at 8 positions and two elevations within the building (see fig. 2) in winter, (A) at the elevation of 4 feet above the slatted floor; (B) at an elevation of 6 feet above the slatted floor. Error bars are standard deviations.
The predicted ammonia concentration in winter condition was a time-averaged value from 6 cases with different outdoor temperature and aeration strategies (Table 4-11). Both CFD models and measurements showed that ammonia was not evenly distributed in the pig area (Figure 5.44 – 5.49). Ammonia concentrations were higher at the locations far away from the fan outlet than near the fan. The two-way ANOVA analysis showed the ammonia distribution in the pig space was significantly associated to the sampling locations. The $p$-value was less than 0.01. No statistical difference was found between model-predicted ammonia concentration and measured values, which had a $p$-value of 0.6 (Figure 5.51).

Both the predicted and measured temperatures were uniform at 4 feet and 6 feet above the floor of the pig area. The average predicted building temperatures were $27 \pm 1 ^\circ C$ in summer and $19 \pm 1 ^\circ C$ in winter, which were very close to the average measured values of $26 \pm 3 ^\circ C$ in summer and $21 \pm 3 ^\circ C$.

5.5.5 Summary

A three dimensional CFD model of a HRHB was developed and validated that simulates the tridimensional airflow field and ammonia concentration distribution. It provided great details about the airflow velocities, pressures, turbulences and ammonia concentrations throughout the pig space. An advantage of this model was that it required much fewer measurements and observations as compared to a tracer gas or anemometer approach, and that it could be used to study the effects of modifying building design and operational parameters without constructing full scale models. The precision and
accuracy of the model were validated by experimental measurements of ammonia concentrations and temperature.

Compared to the previously developed 2-dimensional model, the 3-D model was simulated with a more realistic geometry and fan placements. The outputs showed the superiority of the 3-D model to the 2-D model in predicting airflow pattern and ammonia distribution. The effect of the exhaust fan locations on ammonia distribution was predicted to be significant in winter. Ammonia concentration appeared higher at the locations far away from the fan outlet than that near the fan. These outputs will help designers to further study fan placements and to achieve an optimum air quality in the pig space. Furthermore, the non-isothermal 3-D models predicted a slightly different airflow pattern than the isothermal 3-D model that did not include hogs and heat transfer processes. Animal bodies and thermal buoyancy appeared to significantly affect the air movement across the pig space in winter. Ammonia concentration in the pig space was predicted to be slightly higher than that from the isothermal models as a result.

However, a word of caution is still needed here. Since this model simulates a time-averaged process, the airflow patterns depicted by the 3-dimensional model may or may not represent the instantaneous situation in the HRHB. In practical operating conditions, the airflow in a HRHB does not achieve a steady state. It is affected by many factors including temperature, outside wind velocity and direction, air pressure, animal activities, manure production, and the airflow rate distribution above the bedding. Nevertheless, the CFD model can provide large-scale details of a full-field, time-averaged airflow field and ammonia distribution in the HRHB. The outputs can help to
better understand the airflow in the building and improve current designs. It can be used to study the effects of modifying building design and operational parameters without building a full scale model.

5.7 Modification of Ventilation System

The different aeration conditions had been modeled in the earlier validation work (Figure 4.44 – 4.49). The average ammonia concentration at 0.6 m (2 feet) above the second floor was calculated by integral of ammonia concentration on this elevation and divided by the area. The results showed that the air used to dry the manure bedding could flow up to the upper level of the building and result in higher ammonia concentration in the pig space (Figure 5.52). Thus, the aeration used to dry manure bedding should be limited if good air quality is achieved in the upper level of the HRHB.

However, the aeration was a critical part of the HRHB, which was used to dry the manure and eliminate the liquid storage. The previous work had showed that no liquid drainage was found when using continuous aeration. The moisture content of manure bedding was around 65%, which was good for composting process (Keener et al, 2000). While the farmer used intermittent aeration strategies, some amount of liquid drainage from the building was reported (Keener et al., 2003). Liquid waste management had to be used to reduce the pollution to environment. But an air quality benefit and lower power cost were achieved. Therefore, the offset of different strategies should be considered and evaluated before the highest benefits and lowest pollution were obtained.
Figure 5.52 Predicted area weight average ammonia concentrations at 0.6 m (2 feet) above the second floor in an occupied HRHB.
The effect of inlet size on air velocity and airflow pattern in the building was also investigated using the 3D non-isothermal CFD models. With the inlet baffle moving down from 6 mm to 10 cm away from the ceiling, air velocities entering the building dropped rapidly from 2.7 m/s to 0.2 m/s in winter. Cold air leaving the ceiling inlet traveled farther with high inlet air velocities than that with low ones after it met the warm room air (Figure 5.39 & 5.53). Under the condition that the inlet size was 10 cm, the warm airflow driven by the thermal buoyancy effect above the animals dominated the airflow pattern in the building (Figure 5.53). A large airflow cycle was formed above the pig space; cold air entering the building, pushed by warm air, flowing to the center of building and downward to the pig space, then flowing over the pig space and going upward before reaching the wall, and finally mixing with cold inlet air again. This airflow pattern led to a significant ammonia and temperature gradient across the pig space (Figure 5.54 & 5.55). The lowest ammonia concentration (20 ppm) in the upper level of the build was found above the walkway. The highest ammonia concentration was 34 ppm at the locations near the sidewall and the exhaust fan. The average ammonia concentration at the elevation of 0.6 m above the second floor was estimated as 26 ppm. The temperatures were predicted in a range from 13°C to 21°C. Some areas near the walkway had temperatures lower than the optimal temperature for hogs (18°C).

When the inlet size was 6 mm, the air was well mixed above animal space. The air convection forced by the inlet airflow dominated the airflow pattern even though the thermal buoyancy effect was significant. The room temperatures were predicted as much more even distributed as compared to those with the large ceiling inlet (10 cm). The
Figure 5.53: Air velocity vector distribution on a plane across the fan outlet for winter condition in an occupied High-Rise™ hog building. Ceiling inlet size was 10 cm. Arrow size and length are proportional to air velocity. Some arrows are outside the Figure boundary.
Figure 5.54: Temperature contour for winter condition in an occupied HRHB. Ceiling inlet size was 10 cm. Outdoor temperature was 0°C. The plane is 2 feet above the slatted floor in the building.
Figure 5.55: Concentration contour of ammonia (ppm) for winter condition in a HRHB. The aeration fans were turned on. The outdoor temperature was 0°C. The plane about 2 feet high from the slatted floor in the building is selected to show the ammonia distribution throughout the airspace near the pigs.
average ammonia concentration at the elevation of 0.6 m above the second floor was approximately 24 ppm which was slightly lower than that (26 ppm) using the large ceiling inlet (10 cm) (Figure 5.40). Thus, considering both ammonia and temperature distribution in the pig space, a large ceiling inlet opening should be avoided during the minimum ventilation period in winter.

Ammonia had been found not evenly distributed in the pig area in winter. The pens that were furthest from the exhaust fan exhibited the highest ammonia concentrations. In order to achieve a lower and more even distributed ammonia distribution in the pig space, designers and operators expected that using more small exhaust fans in winter could move more contaminant air out from the building. In this study, two winter cases were simulated; one was the previous HRHB that used 6 small fans during the minimum ventilation period, the other was a similar HRHB but used 12 small fans. The total air change rate was kept same as 5 air changes per hour in both cases.

The 3D non-isothermal CFD models were developed to study the effect of exhaust fan numbers on the airflow pattern in the HRHB. An average ammonia concentration was predicted across the pig space. However, unfortunately, the output of CFD models did not meet the expectation of designers. The CFD models predicted that more ventilation fans could not significantly reduce ammonia concentration in the building. The average ammonia concentration (24.3 ppm) at 0.6 m above the slated floor with 12 small fans was not significantly different from that with 6 small fans (24 ppm) (Figure 5.56). No air blown through the manure bedding flowed up to the upper level
(Figure 5.57). However, some air entering the lower level from the upper story flowed back into the pig space, which led to high ammonia concentrations in some animal areas (Figure 5.56 & 5.58). If the equipment and electricity cost are included, the installation of more small fans in the HRHB is not appropriate.
Figure 5.56: Concentration contour of ammonia (ppm) for winter condition in a HRHB with 12 small fans. The aeration fans were turned on. The outdoor temperature was 0°C. The plane about 2 feet high from the slatted floor in the building is selected to show the ammonia distribution throughout the airspace near the pigs.
Figure 5.57 Predicted airflow pathlines starting from surface of the manure bedding for winter condition in an occupied HRHB with 12 small fans. The aeration fans were turned on. The outdoor temperature was 0°C.
Figure 5.58 Predicted airflow pathlines starting from ceiling inlet for winter condition in an occupied HRHB with 12 small fans. The aeration fans were turned on. The outdoor temperature was 0°C.
CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

A theoretical and experimental study has been done and used to evaluate the nutrient management and air quality in a High-Rise™ Hog Building (HRHB) and associate manure management system. The nutrient losses from the system were determined with mass balance analysis. Ammonia concentrations in the pig space and ammonia emissions from the building were regularly monitored. Computational Fluid Dynamics (CFD) models were developed and validated to investigate airflow pattern and ammonia distribution in HRHB. The non-isothermal CFD models were further used to optimize the ventilation system of HRHB.

Experiments were conducted at a commercial HRHB located in Darke County, OH. Two groups of hogs, 998 head in summer and 1047 head in winter were studied. Animals grew well with an average weight gain rate of 0.86 kg/pig/day (1.89 lb/pig/day). The feed was consumed at a rate of 2.4 kg/pig/day (5.3 lb/pig/day). The average conversion ratio of feed was about 2.83. At the start of the experiment, sawdust bedding
was added at a rate of 45 kg/pig to absorb the moisture from the manure in the lower story. During growth, manure accumulated at an average rate of 0.63 kg/head/day.

The average nitrogen, phosphorous and potassium losses from the HRH building in both summer and winter periods were 3.86 kg/head, 0.25 kg/head and 0.76 kg/head, representing 52, 21, 47% of the initial respectively due to the volatilization (N) and liquid drainage (N, P, K). After manure was removed from the building and composted, most N, P and K were conserved in the final compost product. Only 17% nitrogen, 3% phosphorus, and 4% potassium from the initial manure/amendment mixture was lost throughout a 100 days composting process. In total, about 57, 22, and 48% of the total N, P, K inputs (including the part from the amendment for composting process) were lost from the whole HRHB system including both building losses and composting losses.

Ammonia concentrations in HRHB were measured at two elevations of 1.2 m and 1.8 m above the second floor every other week during summer and winter production cycle. The results showed that in summer ammonia concentration never exceeded 2.5 ppm in the pig space. In winter, the average ammonia concentration was 16 ± 6.32 ppm in the pig space. The highest ammonia concentration was measured approximate 30 ppm on Dec 4th when the outdoor temperature was below -4°C (25 F).

A one-way ANOVA model and two linear regression models were developed to show the relationship between ammonia concentration in the pig space and outdoor temperature or indoor/outdoor temperature difference. The \( p \)-values were calculated less than 0.001. Higher ammonia concentrations were found with lower outdoor temperature and higher indoor/outdoor temperature difference. Using the regression models, a critical
outdoor temperature of -5°C and indoor/outdoor temperature difference of 23°C were predicted over which ammonia concentration in the pig space could exceed the threshold limit value (TLVs) of 25 ppm.

Two-dimensional CFD modeling allowed rapid simulation of airflow and ammonia concentrations in the HRHB. Compared with airflow velocity and ammonia concentrations measured previously, both laminar and turbulent flow models allowed the concentration gradients throughout the building to be predicted. The turbulent flow model better predicted measured ammonia concentration values than the laminar flow model. However, both showed some predict ammonia concentrations deviated (>50%) from the measured values.

Three-Dimensional isothermal CFD models were developed and validated that simulated the 3-D airflow field and ammonia concentration distribution in an empty HRHB. Compared to 2-dimensional model, 3-D model more accurately represented building geometry and operation processes such as exhaust fan placement and airflow distribution across the horizontal area of the animal space. Ammonia was not evenly distributed across the pig space. The pens that were far away from the exhaust fan exhibited higher ammonia concentration.

Three-Dimensional non-isothermal CFD models were also developed and validated to investigate airflow pattern and ammonia distribution in an occupied HRHB. These models predicted that animal bodies and buoyancy effect could significantly affect air movement and ammonia distribution in the building, especially when the outdoor temperature was very low and the indoor/outdoor temperature difference was large. In
winter, the CFD models predicted that some air blown through the manure bed could flow up into the pig space, which could lead to high ammonia concentrations in the upper level of the building. This could be caused by the aeration used to dry manure mix, re-circulation of the airflow in the building or both. Based on the output of the model for winter conditions, optimization of the ventilation system may be needed to improve airflow and reduce ammonia concentration.

Some modifications of the ventilation system of HRHB during winter period were simulated using 3-D non-isothermal CFD models. The aeration used to dry manure bedding was predicted as a significant factor to cause high ammonia concentration in the pig space. Ceiling inlet size was predicted to keep small in winter to achieve an even distributed temperature profile across the pig space. Furthermore, using more small exhaust fans was predicted unnecessary to reduce the ammonia gradient in animal space under the same low air change rate.

This study helped designers and hog producers to deeply understand the system and make full evaluation. Based on this study, a comparative assessment of the HRHB system versus other alternative hog production systems could be developed. CFD modeling could be a powerful tool to investigate airflow pattern and air quality in animal housing. The precision and accuracy of the model were validated by experimental measurements of ammonia concentrations and temperature.
6.2 Recommendations for future research

In the future, this study will be used to make a comparative assessment of the HRHB system versus other alternative hog production systems with the same mass balance analysis. Regulators and animal producers can use nutrient losses from different systems as an important criterion to evaluate the pollution potential of each system.

Ammonia concentrations in the building were measured every other week using Dräger and GASTEC diffusion. The device-measured value was tested in 80-120% of expected value which may limited the accuracy of the research. Using more accurate equipments and continuous measurements can significantly improve the reliability of this study and achieve more information.

Using CFD models to study airflow pattern and ammonia distribution in a HRHB has been proven as a powerful tool. In this study, the CFD models were developed on a personal computer which had limit computation sources. The models only simulated one representative section of the building based on some symmetry assumptions and geometry simplification. These could lead to some deviation of the predicted results from the true airflow state. Furthermore, animals were simply simulated as square boxes. Although animal bodies shapes has been shown that they did not significantly affect the airflow in the building, they could influence the heat transfer and airflow near the animals. To investigate these effects, more fine grids boundary conditions may be needed. Therefore, using super computer or much faster personal computer can allow developing a better CFD model which will simulate the entire building and more detail animal characters.
The CFD models predicted that the airflow used to dry the manure bedding could flow up to the upper level of the building and result in higher ammonia concentration in the pig space. The aeration was expected to be limited to improve air quality. However, the aeration was a critical part of the HRHB, which was used to dry the manure and eliminate the liquid storage. Therefore, the offset of different strategies should be considered and evaluated before the highest benefits and lowest pollution were obtained. A possible solution here may be to use a new design to change airflow directions through the manure bedding to control ammonia release from the manure bedding (Figure 5.53). Slatted floor will be used in the first floor on which bedding materials are still used to accept feces and urine. A few channels are built below the slatted floor and connected to aeration fans. Saturated air will be extracted from the channel, which generate a negative pressure under the floor. Room air will be sucked through the bedding and push ammonia away from the pig space. It will be the next step study for this research.
Figure 5.59: A possible new design for HRHB to change airflow direction through the manure bedding.


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MWPS. 2000. Manure characteristics. MWPS-18, Midwest Plan Service, Iowa State University, Ames, IA.


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AMMONIA CONCENTRATION ON THE SURFACE OF MANURE BEDDING MATERIAL

The ammonia on the surface of manure/bedding material is strongly related to its volatilization which involves two equilibriums, (A1) and (A7). The ammonia-ammonium equilibrium

\[ NH_4^+(l) \Leftrightarrow NH_3(l) + H^+ \]  

(A1)

has an equilibrium constant \( K_a \), which is defined as:

\[
K_a = \frac{[NH_3](l)[H^+]}{[NH_4^+](l)}. 
\]  

(A2)

\[ [H^+] = 10^{-pH} \]  

(A3)

\[ [NH_4^+](l) = [totalNH_3] - [NH_3](l) \]  

(A4)

\([totalNH_3]\) is the total ammonia-ammonium nitrogen concentration in the manure.

Combined equations A1-A4, the liquid ammonia concentration is achieved by

\[
[NH_3](l)/[totalNH_3] = 10^{pH} K_a / (K_a 10^{pH} + 1) 
\]  

(A5)

For hog manure,

\[
K_a = 10^{-0.09018 + \frac{2728.92}{T}} \]  

(Ni, 1999)  

(A6)

The other equilibrium occurs at the interface of gas and liquid,
\[ [NH_3](l) \rightleftharpoons [NH_3](g), \quad (A7) \]

which follows Henry’s law since ammonia concentration is low.

\[ P_{[NH_3](g)}(atm) = K_h[NH_3](l)(mol/l) \quad (A8) \]

\( P_{[NH_3](g)} \) is the partial pressure of ammonia. \( K_h \) is Henry’s constant,

\[ \ln K_h = 160.559 - \frac{8621.06}{T} - 25.6767 \ln T + 0.0353887 \ln T, \quad (Ni, \ 1999) \quad (A9) \]

Combined equations (A5), (A6), (A8) and (A9), the partial pressure of ammonia gas on the surface of manure can be calculated (Table A.1-2) (Figure A.1-2)
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Table A.1: Ammonia (liquid and gas) concentration on the surface of manure bedding material in winter condition. Average surface temperature of manure bedding was 20°C, with a range from 17 to 22°C. Ka was 3.91 x 10⁻¹⁰ calculated by equation (A6). Average ammonia nitrogen was measured 1.3% of dry matter, which was 30% of the total weight. The bulk density of manure/bedding material was 554 kg/m³. The ammonia concentration in the manure was 0.155 mole/l. K₅H equals 0.0135 calculated from equation (A9).
Figure A.1: Partial pressure of ammonia (gas) on the surface of manure bedding material in winter condition. Average surface temperature of manure bedding was 20°C, with a range from 17 to 22 °C. Ka was 3.91 x 10^{-10} calculated by equation (A6). Average ammonia nitrogen was measured 1.3% of dry matter, which was 30% of the total weight. The bulk density of manure/bedding material was 554 kg/m³. The ammonia concentration in the manure was 0.155 mole/l. K_h equals 0.0215 calculated from equation (A9).
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Table A.2, Partial pressure of ammonia on the surface of manure bedding material in summer condition. Average surface temperature of manure bedding was 30°C, with a range from 27 to 32 °C. Ka was 7.95 x 10⁻¹⁰ calculated by equation (A6). Average ammonia nitrogen was measured 0.97% of dry matter, which was 25% of the total weight. The bulk density of manure/bedding material was 566 kg/m³. The ammonia concentration in the manure was 0.10 mole/l. $K_h$ equals 0.0215 calculated from equation (A9).
Figure A.2: Ammonia (liquid and gas) concentration on the surface of manure bedding material in summer condition. Average surface temperature of manure bedding was 30°C, with a range from 27 to 32 °C. Ka was $7.95 \times 10^{-10}$ calculated by equation (A6). Average ammonia nitrogen was measured 0.97% of dry matter, which was 25% of the total weight. The bulk density of manure/bedding material was 566 kg/m$^3$. The ammonia concentration in the manure was 0.10 mole/l. $K_h$ equals 0.0135 calculated from equation (A9).

REFERENCE:

APPENDIX B

THE INERTIAL LOSS FACTOR THROUGH A SLATTED FLOOR

Pressure change through a thin porous medium with a finite thickness can be defined as a combination of Darcy Law and an additional inertial loss term (FLUENT, 1998).

$$\Delta p = -\left(\frac{\mu}{\alpha} v + C_2 \frac{1}{2} \rho v^2\right) \Delta m$$

(B1)

where $\Delta p$ is the pressure drop through the media, $\mu$ is the viscosity of air, $\alpha$ is the permeability, $C_2$ is the inertial loss factor, $\rho$ is air density, $v$ is air velocity and $\Delta m$ is the thickness of the porous media.

When modeling a perforate plate or tube bank, the permeability term is negligible (FLUENT, 1998). The inertial loss term, which represents the airflow dynamic head loss through the porous media, is usually used alone.

In this study, the 10 cm thick slatted floor with slots of 2.54 cm (1 inch) every 17.8 cm (7 inches) was simplified for modeling purpose, as a perforate plate.

$$\Delta p = -C_2 \frac{1}{2} \rho v^2 \Delta m$$

(B2)
The Fluent manual presents several procedures to determine the inertial loss factor $C_2$ (Fluent, 1998), which provides more options for researchers to use the optical approach to get the objective factors.

The first procedure is based on superficial velocity and known pressure loss. Consider a slatted plate which has 14% area open (slots of 2.54 cm every 17.8 cm) to flow. The pressure drop through the plate and superficial velocity in the slots are known as $\Delta p$, $v_{14\%\text{open}}$. The loss factor $K_{\text{loss}}$ defined as

$$
\Delta p = K_{\text{loss}} \frac{1}{2} \rho v_{14\%\text{open}}^2
$$

(B3)

can be calculated.

To compute an appropriate value of $C_2$, two assumptions should be clarified first.

(1) The velocity in equation (B1) and (B2) is that of assuming the plate is 100% open,

(2) The loss coefficient must be converted into dynamic loss per unit length of the porous media.

Under the first assumption, the adjust loss factor $K_{\text{loss}}'$, which would be based on the velocity of a 100% open area, can be calculated from:

$$
\Delta p = K_{\text{loss}}' \frac{1}{2} \rho v_{100\%\text{open}}^2
$$

(B4)

Thus,

$$
K_{\text{loss}}' = K_{\text{loss}} \frac{v_{14\%\text{open}}^2}{v_{100\%\text{open}}^2}
$$

(B5)

Noting that for the same flow rate, $v_{14\%\text{open}} = 7 \times v_{100\%\text{open}}$,

$K_{\text{loss}}' = 49 \times K_{\text{loss}}$
Based on the second assumption and equation (B2)-(B4), the inertial loss factor is

\[ C_2 = \frac{K'}{\text{thickness}} \]  \hspace{1cm} (B6)

This factor must be computed for each of the 2 (or 3) coordinate directions.

In this study, the air velocity was low (0.03-0.2 m/s) through the slatted floor in winter. The Reynolds number (Re) calculated using the slot width was lower than 1000, which indicated that the air passing the floor is a laminar flow. The pressure drop across the floor was too low (about $10^{-3}$-$10^{-2}$ pascal) to measure. Thus, a modeling method was used to determine the pressure drop through the slatted floor.

As shown in Fig. B.1, one part of the slatted floor was modeled. A 2-dimensional geometry (5.08 m x 0.09 m) was developed and meshed using GAMBIT software provided by Fluent (Figure B2). The air velocity in the slot, pressure drop through the floor as well as inertial loss factor were computed from computational fluid dynamic (CFD) laminar airflow models (Table B.1)
Figure B.1 Modeling slatted floor
Figure B.2 Meshed geometry and boundary conditions used in the model

<table>
<thead>
<tr>
<th>Air velocity in the slots (m/s)</th>
<th>Pressure drop (Pa)</th>
<th>Inertial loss factor (m⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>0.0019</td>
<td>608</td>
</tr>
<tr>
<td>0.10</td>
<td>0.0072</td>
<td>576</td>
</tr>
<tr>
<td>0.15</td>
<td>0.016</td>
<td>569</td>
</tr>
<tr>
<td>0.20</td>
<td>0.028</td>
<td>560</td>
</tr>
</tbody>
</table>

Table B1 Predicted pressure drops and inertial loss factors according to air velocity through the slatted floor with a porosity of 14%.
The other method to derive the inertial loss factor is using the equations of Van Einkle et al. (Perry et al., 1984; Smith and Van Winkle, 1958; Fluent, 1998), which is suitable for turbulent flow through a perforate plate.

In this study, the air velocities through the slatted floor in summer was more than 10 times of those in winter. The Reynolds number was larger than 4000, which resulted in that the laminar flow model could not be validated to compute the inertial loss factor. However, the empirical equation of Van Einkle et al. provided a much easier way to obtain these factors. To use this equation, an assumption must be made first that the slatted floor was very similar as a perforated plate with square-edged holes. Under this assumption, the constant $C_2$ can be calculated from

$$C_2 = 1 - \left( \frac{A_p}{A_f} \right)^2 \left( \frac{C}{C^2} \right)$$

(B7)

$A_p$ is the area of the plate (solid and holes), $A_f$ is the free area or total area of the holes, $t$ is the thickness of the plate, and $C$ is a coefficient which has been tabulated for various Reynolds-number range and for various $D/t$ (the ratio of hole diameter (slot width) to plate thickness). For $t/D > 1.6$ and $Re > 4000$, the coefficient $C$ takes a value of approximately 0.98.

Thus, the inertial loss factor for summer conditions was calculated as $C_2 = 499$.

REFERENCE:

Smith and Van Winkle, 1958, AICHE J., V. 4, pp. 166-168
APPENDIX C

TEST OF AMMONIA DIFFUSION TUBES

Ammonia diffusion tube provides the measurement of the mean value of ammonia in air by the principle of gas diffusion and colorimetric reaction. No air sampling equipment such as pump, motor driven air sampler is needed. The sampling usually takes a few hours. The average ammonia concentration is calculated from the length of discolors zone (the indication “ppm x hours”) and the exposure time.

\[
\text{Ammonia concentration (ppm)} = \frac{\text{Detector tube indication (ppm x hours)}}{\text{Actual sampling time}}.
\]

In this study, three diffusion tubes were used; these being Dräger diffusion tube, 2.5-1500 ppm, GASTECH Dosimeter diffusion tube, 0.1-10 ppm and GASTECH Dosimeter diffusion tube 2.5-1000 ppm.

Dräger tube has a maximum measuring time of 8 hours. The results of the measurement are not sensitive to the temperature within the range of 0°C and 40°C, and humidity within the relative humidity range of 5 to 95%. However, air pressure can influence the tube reading significantly. For pressure correction, a conversion factor may be needed to multiply the tube reading.

\[
\text{Conversion factor} = \frac{1013 \text{ mbar}}{\text{actual air pressure (in mbar)}}.
\]
GASTEC tube has different sensitivity. No correction for pressure and humidity within relative humidity range of 20-90% are required. However, the tubes are sensitive to the temperature. To correct for temperature, the tube reading should multiply some reaction factors (Table C1). The different sensitivities of Dräger and GASTEC diffusion tubes provide more options for researchers to use the right tubes under different environment, such as temperature and air pressure.

<table>
<thead>
<tr>
<th>Average temperature (°C)</th>
<th>Correction factor</th>
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</thead>
<tbody>
<tr>
<td>0</td>
<td>1.25</td>
</tr>
<tr>
<td>10</td>
<td>1.1</td>
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<td>20</td>
<td>1.0</td>
</tr>
<tr>
<td>30</td>
<td>0.92</td>
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<tr>
<td>40</td>
<td>0.84</td>
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</table>

Table C.1 Correction factors of GASTEC tube at different temperatures
Both Dräger and GASTEC tubes were tested for their reliability and reproducibility. A calibration ammonia gas of 50 ppm was used. The test experiment design is shown in Figure C.1. The ammonia gas flow rate was about 60 ml/min. The results were presented in Figure C.2-C.4. The error of the measurement of diffusion tubes was limited in 20%.

Figure C.1 Test of diffusion tubes for their reliability and reproducibility by using a 50 ppm ammonia calibration gas.
Figure C.2 Test of GASTEC diffusion tubes (SKC Inc., 2-1000 ppm) with a calibration ammonia gas of 50 ppm
Figure C.3 Test of Dräger (SKC Inc., 2.5-1500 ppm) diffusion tubes with a calibration ammonia gas of 50 ppm
Figure C.4 Test of GASTEC diffusion tubes (SKC Inc., 1-10 ppm) with a calibration ammonia gas of 50 ppm