JAIRO ALEXANDER OSORIO SARAZ

MEASUREMENT AND CFD MODELING OF AMMONIA CONCENTRATION, FLUX AND THERMAL ENVIRONMENT VARIABLES IN OPEN SIDE BROILER HOUSING

Tese apresentada à Universidade Federal de Viçosa, como parte das exigências do Programa de Pós-Graduação em Engenharia Agrícola, para obtenção do título de *Doctor Scientiae*.

VIÇOSA
MINAS GERAIS – BRASIL
2010

Ficha catalográfica preparada pela Seção de Catalogação e Classificação da Biblioteca Central da UFV

T
O83m
2010

Osorio Saraz, Jairo Alexander, 1975-
Measurement and CFD modeling of ammonia concentration, flux and thermal environment variables in open side broiler housing / Jairo Alexander Osorio Saraz. – Viçosa, MG, 2011.
xv, 115f. : il. (algumas col.) ; 29cm.

Orientador: Ilda de Fátima Ferreira Tinôco.
Tese (doutorado) - Universidade Federal de Viçosa.
Inclui bibliografia.

1. Indústria avícola - Instalações. 2. Frango de corte. 3. Poluição - Aspectos ambientais. 4. Ventilação. 5. Ar - Teor de amônia. 6. Fluídos - Simulação por computador. I. Universidade Federal de Viçosa. II. Título.

CDD 22. ed. 631.2

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APROVADA: 06 de dezembro de 2010.

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A Dios.

A Olga y Gerónimo quienes son mi vida.

A mis padres, hermana y mi sobrino Sebastián.

AGRADECIMENTOS

A Deus, por todas as graças que proporciona a mim e à minha família.

À professora Ilda de Fátima Ferreira Tinôco, pelo apoio, pela confiança, pela amizade e por ter sido parte fundamental no alcance de meus objetivos.

Ao professor Márcio Arêdes Martins, pelos ensinamentos, pela amizade e por despertar o meu interesse na área da Dinâmica dos Fluidos Computacional (CFD).

Ao professor Richard Gates, pela amizade e pela oportunidade de obter novos espaços na minha vida pessoal e profissional.

Ao professor Jadir Nogueira da Silva, pela amizade e pelos ensinamentos.

Aos professores Sérgio Zolnier, Fernando da Costa Baêta e José Helvécio Martins, pelos ensinamentos.

Ao Dr. Ricardo P. Roberti, da Pif-Paf Alimentos.

À Universidade Nacional de Colômbia Sede Medellín, em especial ao Departamento de Engenharia Agrícola e de Alimentos.

À Colciencias Colômbia, pela concessão da bolsa de estudos.

À Universidade Federal de Viçosa e ao Departamento de Engenharia Agrícola, pela oportunidade de realização do curso.

Aos amigos que foram minha família no Brasil e que sempre farão parte de minha vida: Marcos, Keller, Jofran, Flávio, Fábio, Neiton, Maria Clara, Akemi, Adriana, Conceição, Betty, Débora, Roque, Irene, Marcelo, Fernanda,

Luciano, Cinara, Pedro, Samuel, Marilu, Damiana, Alexandre, Marcos Magalhães, Fatinha, Michel e Kelles. Aos meus sobrinhos brasileiros Arthur e Laura, e colombianos Verônica, Fernando, Juan Jose, Juan Camilo, Esteban, Sofia e Daniela.

Aos meus compadres colombianos que juntos formaram uma família em Viçosa: Enrique, Ketty, Nelson, Jenny, Sebastian, Carolina, Zulma e Alonso e Lina e Robinson.

BIOGRAFIA

JAIRO ALEXANDER OSORIO SARAZ, filho de Hector Jairo Osorio Arenas e Angela Maria Saraz Hernandez, nasceu na cidade de Medellín Colombia, Departamento de Antioquia, em 28 de junho de 1975.

Em 1992, iniciou o curso de Engenharia Agrícola pela Universidade Nacional de Colômbia, graduando-se em dezembro de 1998.

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SUMÁRIO

RESUMO

OSORIO SARAZ, Jairo Alexander, D.Sc., Universidade Federal de Viçosa, dezembro de 2010. **Medições e modelagem em CFD de concentrações de amônia, fluxos e variáveis ambientais em galpões avícolas abertos**. Orientadora: Ilda de Fátima Ferreira Tinôco. Coorientadores: Márcio Arêdes Martins e Richard S. Gates.

A amônia (NH_3), dentre os diversos gases poluentes gerados de produção avícola, aquele mais investigado e considerado de maior importância, devido a seu efeito negativo na saúde e produtividade dos trabalhadores e dos animais. Apesar das pesquisas já terem trazido avanços significativos em termos de medidas mitigadoras ou minimizadoras da taxa de emissão de NH_3 gerada nos aviários, naturalmente sempre se terá uma geração deste tipo de gases, os quais necessitam constante avaliação em termos quantitativos e de impactos. Existem diversas metodologias para se determinaram a emissão de amônia proveniente da cama aviaria e emitida através do galpão, destacando-se métodos de traçado de gases, métodos de monitoramento continuo, balanço de massas, entre outros. Todos estes métodos têm boas eficiências quando são usados em estruturas fechadas, típicas de países da Europa e America do norte. No entanto, a aplicação destes métodos visando determinação de emissões ou fluxos de amônia tem maior grau de dificuldade em estruturas avícolas que funcionam abertas durante a totalidade ou parte do dia, fazendo uso da ventilação natural. Assim, o objetivo, geral deste projeto foi de adaptar e validar um método simples para determinar a distribuição de fluxo de amônia oriunda da cama e emitida pelo aviário, da distribuição da concentração deste gás no ar, bem como a distribuição da temperatura e velocidades do ar em galpões avícolas tropicais e subtropicais para frangos de corte. Especificamente visou-se: i) Avaliar quanto a aplicabilidade dos principais métodos atualmente usados para a determinação de emissões de amônia gerada nos aviários fechados de frango de corte, e adaptar e avaliar um método, e analisar sua aplicabilidade em instalações abertas praticadas em países de clima tropical e subtropical; ii) Adaptar e validar uma metodologia para determinar o fluxo de amônia gerada por cama sobreposta praticada na avicultura de corte e outras; iii) Realizar medidas da concentração de amônia, da temperatura e da velocidade de ar no interior de aviários abertos, com base em trabalho experimental; iv) Desenvolver e validar um modelo computacional, usando como ferramenta a Dinâmica de Fluidos Computacional (CFD), para determinar a distribuição de temperatura, de concentração de amônia, e de velocidade do ar no interior do galpão. Para determinar o fluxo de amônia da cama aviária e emissão emitida pelo galpão, foi adaptada e validada uma metodologia ao mesmo tempo precisa e de simples aplicação denominada "Método Saraz para Determinação de Emissões de Amônia" (Saraz Method for Determination of Ammonia Emissions - SMDAE). Encontrou-se que os valores de fluxo obtidos pelo SMDAE não diferem dos reportados por outros trabalho, e que a metodologia pode ser usada para valores de concentrações de amônia maiores que 0,5 ppm no caso da cama. O método SMDAE, foi adaptado e validado para determinar o fluxo de NH_3 emitida pelas laterais dos galpões avícolas submetidos à ventilação natural. Verificou-se que o método proposto pode ser usado com confiabilidade em condições de ventilação natural com ventos maiores que 0,1 m s^{-1} e concentrações de NH_3 maiores que 1 ppm. Uma avaliação quantitativa mostrou que os métodos com maiores características de adaptabilidade as condições de operação e aos diferentes tipos de acondicionamento de ambiente de galpões com sistemas de ventilação de pressão positiva ou com ventilação natural, são o método de traçado de gases interno e o de Unidades de Monitoramento Contínuo como a Unidade Portátil de Monitoramento (PMU) e Unidade Móvel de Monitoramento de

Emissões no ar (MAEMU). Métodos tais como o método baseados em balanços de massas e aqueles de difusão passiva como o “Ferm Tube” e o SMDAE, indicam também poderem ser adaptados para as diferentes condições de operacionalidade dos galpões abertos. Com os dados experimentais de fluxo de amônia da cama aviaria obtidos pelo método SMDAE, de concentração de amônia, de velocidade do ar e de temperatura, foi aplicado e validado um modelo em Dinâmica dos Fluidos Computacional (CFD). Encontrou-se que o modelo teve uma boa correlação estatística com os dados experimentais, pelo qual este pode ser usado para predizer num tempo real o comportamento da distribuição de concentrações de NH_3, de velocidade do ar e de temperatura, no interior de instalações abertas com ventilação natural e com ventos incidentes e diferentes direções de entrada na lateral da instalação.

ABSTRACT

OSORIO SARAZ, Jairo Alexander, D.Sc., Universidade Federal de Viçosa, December, 2010. **Measurement and CFD modeling of ammonia concentration, flux and thermal environment variables in open side broiler housing**. Adviser: Ilda de Fátima Ferreira Tinôco. Co-advisers: Márcio Arêdes Martins and Richard S. Gates.

Ammonia (NH_3), among the various gas pollutants generated from poultry production, is that most investigated and considered of greatest importance due to its negative effect on health and productivity of both workers and animals. Although research studies have already brought about significant advances in terms of mitigation measures or minimization of the NH_3 emission rate generated in aviaries, there will always be a generation of such gases, which require constant evaluation in terms of quantity and impacts. There are several methodologies used to determine the emission of ammonia produced from the litter bedding and emitted from the installation, especially methods of tracer gases, methods of continuous monitoring, mass balance and others. All these methods are efficient when used in enclosed structures, typical of countries in Europe and North America. However, the application of these methods for determination of ammonia emission fluxes has a higher degree of difficulty in poultry facilities which operate open during all or part of the day, making use of natural ventilation. Thus, the objective of this project was to adapt and validate a simple method to determine the distribution of ammonia flow derived from the bed and emitted by the poultry house, the concentration distribution of this gas in the air, and the distribution of temperature and air velocities in broiler houses located in tropical and subtropical regions. Specifically it was sought to: i) Assess the applicability of the principal methods currently used for the determination of ammonia emissions generated in closed poultry broiler, and adapt and evaluate a method to analyze its applicability in open installations in countries tropical and subtropical climates, ii). Adapt and validate a methodology for determining ammonia flux generated by litter in poultry production and other activities; iii) Perform measurements of ammonia concentration, temperature and air velocity inside the open poultry installations, based on experimental work, iv). Develop and validate a computational model, using computational fluid dynamics (CFD) to determine the distribution of temperature, ammonia concentration and air velocity inside the building. To determine the flow of ammonia emission from poultry manure and emission by the installation, a precise and simple methodology called the Saraz Method for Determining Ammonia Emissions (SMDAE) was adapted and validated. It was found that the flow values obtained by the SMDAE did not differ from those reported by other works, and that the methodology can be used for ammonia concentrations greater than 0.5 ppm in the case of the bedding. The SMDAE method was adapted and validated to determine the NH_3 flux emitted by the lateral openings of poultry buildings submitted to natural ventilation. It was verified that proposed method may be reliably used in natural ventilation conditions with wind speeds greater than 0.1 m s^{-1} and NH_3 concentrations greater than 1 ppm. A quantitative evaluation showed that methods with greatest adaptability characteristics for the operating conditions and the different types of acclimatization systems with positive pressure ventilation or natural ventilation, are the method of internal tracer gases and Continuous Monitoring Units such as the Portable Monitoring Unit (PMU) and the Mobile Air Emissions Monitoring Unit (MAEMU). Methods such as those based on mass balances and those of passive diffusion such as the "Ferm Tube" and the SMDAE, indicate they can also be adapted for different operating conditions of open poultry houses. With the experimental data of ammonia flow from the poultry litter obtained by the SMDAE, ammonia concentration, air speed and temperature, a model in Computational Fluid Dynamics (CFD) was applied and validated. It was found that the model had a good statistical correlation with the experimental data, so that it may be used for real time prediction of distribution behavior of NH_3 concentrations, air velocity and temperature inside the open facilities with natural ventilation, subjected to different incident winds and entrance directions at the side of the facility.

GENERAL INTRODUCTION

In livestock buildings airborne contaminants originate mainly from the decomposition of organic material. Inhalation of these organic particles and vapors can lead to respiratory diseases in humans and animals. Thus, problems with air quality in animal facilities must be viewed from two aspects:

- First, the pollutants can cause direct alterations in the animal due to the agent-organism interaction (mechanical irritation, local inflammation etc.), being harmful alone as well as preparing the attacked tissue for installation of new diseases.
- Secondly, the excess of certain components can cause stress to the animal, leading to a decline in immune status, and consequent predisposition to disease, as well as decline in productive and reproductive performance.

Additionally, the air quality in animal production systems is directly related to the metabolism of these animals, which release into the air: heat, humidity and carbon dioxide (CO_2), via respiration and gases resulting from digestion and wastes, such as ammonia (NH_3), methane (CH_4), hydrogen sulfide (H_2S), dust, and gases from incomplete combustion for heating, such as carbon monoxide (CO) and nitrous oxide (NO_2), with concentrations often greater than those allowed by norms of the National Institute for Occupational Safety and Health – NIOSH (2001).

Of these gases, NH_3 is the toxic pollutant most frequently encountered within the animal shelters which harms health and reduces the productivity of animals and workers. Additionally, from the processes of nitrification and denitrification, ammonia can be converted into a greenhouse gas, and emissions from the livestock sector contribute to the detriment of air quality.

As a consequence, from the sources related to animal production (systems of housing, manure storage, etc.), ammonia (NH_3) emissions to the atmosphere have increased dramatically. The emission of NH_3 resultant of agricultural activities in Europe excluding the former USSR, doubled between 1950 and 1986 (ASMAN et al., 1988), in the Netherlands, the increase was 2.5 times greater over the same time period (APSIMSON et al., 1987).

This increase in NH_3 emissions has contributed significantly to the deposition of critical levels of nitrogen (N) in soil in many European countries, leading to eutrophication and acidification of soils (HEIJ; SCHNEIDER, 1991; HEIJ; ERISMAN, 1997). In Holland, for example, about 46% of the potential acid deposition is caused by the emission of NH_3, mainly from agriculture (ANONYMOUS, 1996).

Based on these facts, the study of ammonia for years has drawn the attention of researchers from different regions of the world. In Europe and the United States, inventories of NH_3 emissions generated from the livestock sector have already been performed, with emphasis on the production of poultry, pigs and cattle. For closed structures, typical of Europe and the United States, studies have been performed since 1980, reporting the distribution of NH_3 concentrations in the structures and methods used to determine emissions (TINÔCO et al., 2008; GATES et al., 2008; FAULKNER et al., 2008).

Among the existing methodologies for determination of ammonia emissions, those based on tracer gases, mass balances (VRANKEN et al., 2004; TEYE; HAUTALA, 2008; KIM et al., 2008; REIDY et al., 2009), as well as continuous monitoring with the Portable Monitoring Unit (PMU) and the Mobile Air Emissions Monitoring Unit (MAEMU) (AMARAL, 2007; GATES et al., 2005) have been the most used and mainly applied in closed installations.

In regions of tropical and subtropical climates, such as Brazil, basically all the facilities used for intensive production of broilers and other animals of economic interest operate much of the time open with natural or forced ventilation.

A common factor for the employment of conventional methods used in closed installations, when applied to determine ammonia emissions in open buildings, is that although they are efficient for determining NH_3 emissions, they are laborious processes.

Therefore, the objective of this study was to adapt and validate a simple method for determination of ammonia flow distribution produce by the bedding and emitted by the aviary, the distribution of gas concentration in the air, as well as the distribution of temperature and air velocities in broiler houses located in tropical and subtropical regions.

The results of this study are presented in five chapters, where chapters I, II, IV and V are scientific manuscripts and chapter III is a review paper:

- Chapter I: Adaptation and validation of a methodology for determination of ammonia flux generated by the bedding of naturally ventilated aviaries.
- Chapter II: Validation of a methodology to determine ammonia flux generated by aviaries submitted to natural ventilation.
- Chapter III: Evaluation of different methods for determination of ammonia emissions from aviaries and their applicability in open animal production facilities.
- Chapter IV: Employment of 3D CFD for determination of ammonia concentration distribution in non-insulated aviaries with natural ventilation.
- Chapter V: Application of CFD to improve natural ventilation in non-insulated closed aviaries during the night for control of temperature and ammonia concentrations.

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CHAPTER 1

ADAPTATION AND VALIDATION OF A METHDOLOGY FOR DETERMING AMMONIA FLUX GENERATED BY LITTER IN NATURALLY VENTILIATED POULTRY HOUSES

ABSTRACT: The aim of this work was to adapted and validate a precise and simple application method defined as the “Saraz method for determination of ammonia emissions” (SMDAE) which is based on the method of mass diffusion (J $''_A$) to determined the ammonia flux due to mass convection (NA”) from broiler litter. It was found that the ammonia flux (N$''_A$) can be obtained by the diffusion method SMDAE. The SMDAE method presents a recovery efficiency for volatilized ammonia of 77 ± 4% and can be used for ammonia concentrations as high as 0.5 ppm. A statistical model with a reliability of 95% was utilized, which allows for analysis of ammonia flux behavior as a function of parameters such as age of the birds, pH and litter moisture content.
Keywords: Methodologies for ammonia flux, poultry houses, broiler litter, air quality, natural ventilation.

RESUMO: Objetivou-se com este trabalho adaptar e validar uma metodologia ao mesmo tempo precisa e de simples aplicação a ser denominada método Saraz para determinação de fluxo de amônia (SMDAE) o qual é baseado no método de difusão de massa (J$''_A$) para determinar o fluxo de amônia (N$''_A$) devido a convecção de massa das camas aviarias. Encontrou-se que os valores de fluxo de massa de NH_3 podem ser obtidos a partir do método SMDAE de difusão de massa. O método SMDAE teve uma eficiência de recuperação da amônia volatilizada da cama de 77 ± 4% e pode ser aplicada para casos de concentrações de amônia maiores que 0,5 ppm. Um modelo estatístico com uma confiabilidade de 95% foi obtido com o emprego do método SMDAE, o qual permite analisar o comportamento do fluxo de amônia em função de parâmetros tais como idade das aves, pH e umidade da cama.

Palavras-chave: Metodologias para fluxo de amônia, ambiência avícola, cama aviária, qualidade do ar, ventilação natural.

1. INTRODUCTION

Understanding of ammonia emission rates generated in animal confinements from manure is very important, due to its direct relation to negative health effects and productivity of animals and people (TINÔCO, 2004).

Many studied have been developed based on the reduction of ammonia emissions from manure by minimization of nitrogen excretions in the feces due to dietary changes. This procedure constitutes the first step in reducing NH_3 emissions provident of agricultural installations (PANETTA et al., 2006; NDEGWA et al., 2008). However, despite the efficiencies obtained in the technique for reducing ammonia by manipulation of the diets, ammonia emissions cannot be reduced by 100%.

Some methodologies have been developed and validated to determine ammonia gas emissions generated by animal manure, and have been employed in both open and closed animal production installations; however, they obtain different efficiencies in recovery of the total ammonia nitrogen (TAN) which is volatilized.

Among these methodologies, the most utilized are those which involve mass balances, external and internal tracer gas and the passive methods (WELFORD et al., 2003; NICHOLSON et al., 2004; GATES et al., 2005; REIDY et al., 2008; OSORIO et al., 2009; RONG et al., 2009).

The majority of methodologies for ammonia quantification show good performance in closed installations. However, in the case of open installations these methods require adaptations. When using tracer gases, external tracer gases are less efficient compared with internal tracer gases (DORE et al., 2004; PHILLIPS et al., 2000).

The passive flux method requires predominant air flow in the direction of the flux collector, while the greatest difficulty of the mass balance method is encountering the convective mass coefficient (KEENER et al., 2008; TEYE et al., 2008).

Thus, each of the mentioned methodologies present advantages and disadvantages, where a common disadvantage to all is the high cost of operation. Other volatilization models have also been used to predict ammonia emissions based on different circumstances and poultry installation types (AROGO et al., 2003; PINDER et al., 2004). Acquisition of the mass transfer coefficient (h_m), which is an important parameter in the volatilization model of ammonia present in manure, is encountered in literature with ample variation, being a disadvantage of the model.

A methodology used in the study of soils for determining nitrogen (N) loss from the soil by volatilization of TAN makes use of a collector chamber for ammonia fixation by diffusion, where quantification is performed by acid – base titration using the Kjeldhal method (ASSOCIATION OF OFFICIAL ANALITICAL CHEMISTS – AOAC, 1970).

In this methodology, nitrogen recovery efficiencies of roughly 70% are encountered (LARA et al., 1990; YANG et al., 2000; SANGOI et al., 2003; RENATA et al., 2002; LEAL et al., 2007).

Based on these facts, the objective of this study was to obtain the ammonia flux due to mass convection (N''_A) of the broiler litter, using the ammonia mass flux (SMDAE) which is based on the mass diffusion method (J''_A).

2. MATERIAL AND METHODS

The present study was developed in the Laboratories of the Department of Agricultural Engineering, University Federal of Viçosa, Brazil, and in a conventional commercial broiler house integrated with the Pif-Paf Alimentos S/A company, located in the municipality of Viçosa, MG, Brazil.

The climate of the region is, according to the Köppen classification, type Cwb – high altitude tropical with wet summers and pleasant temperatures. This study was performed during the summer, with an average temperature of 22°C and relative humidity varying between 50 and 70%.

2.1. Characteristics of the installation

The commercial poultry house utilized in this investigation housed 14,000 Cobb chickens, with a housing density of 12 birds m^{-2}. Dimensions of the building were 100 m x 13.5 m (Length x Width) with 3 m high ceilings, 0.50 m overhang and 20° roof inclination angle (Figure 1).

The poultry house, with little thermal insulation as is common to Brazil and South America, was open with natural ventilation during the experimental phase and the litter was composed of fresh coffee hulls.

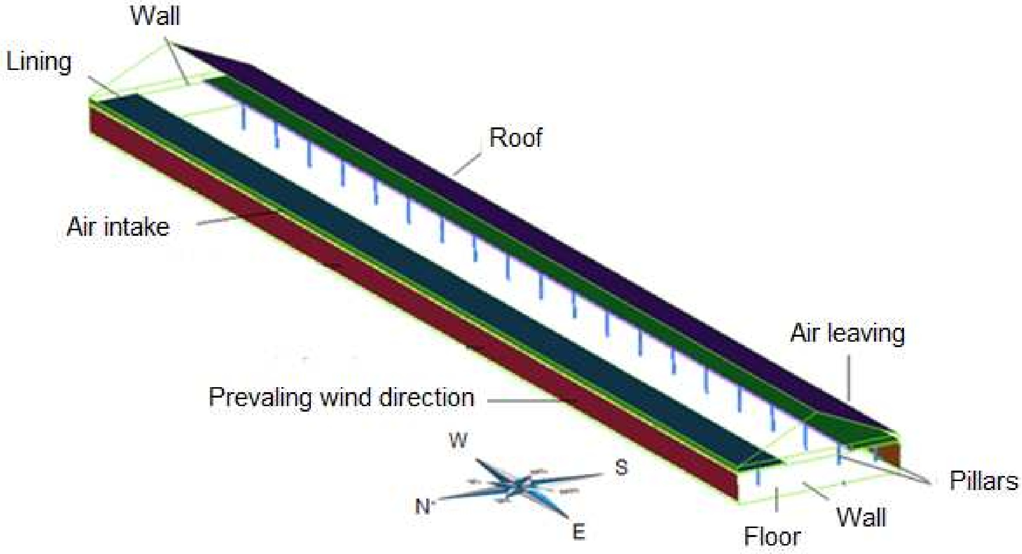

Figure 1 – Characteristics of the experimental installation.

2.2. Mass diffusion method proposed for determining ammonia mass flux denominated SMDAE

A passive flux method used by Renata et al. (2002) and Araujo et al. (2007) was adapted and validated for determining ammonia flux originating from the litter of poultry buildings. This adapted method denominated the "Saraz method for determination of ammonia emissions" (SMDAE), is based on the mass diffusion method for determination of ammonia flux from broiler bedding based on the total volatilized ammonia content that is volatilized and captured.

2.2.1. Measuring equipment

The NH_3 capturing device was constructed from a common PVC pipe measuring 20 cm in diameter and 30 cm in height. Two polyurethane sponges measuring 20 cm in diameter each and 2 cm thick were placed in the tube so that they were 10 (Sponge 1) and 30 cm (Sponge 2) from the base of the PVC collector. The function of sponge 1 was to directly capture the ammonia flux produced by the poultry litter bedding, and sponge 2 is used to prevent contamination by exterior gases which may interfere on the values of ammonia captured by sponge 1 (Figure 2).

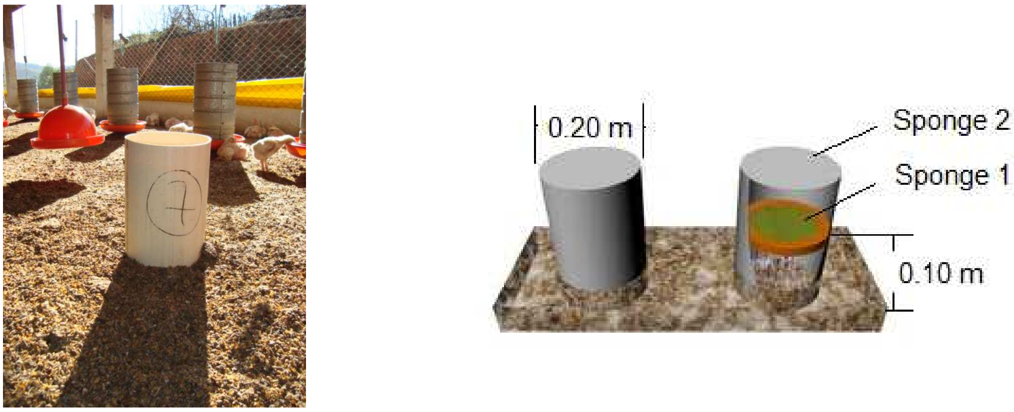

Figure 2 – Collector device used to capture volatilized ammonia.

2.2.2. Appropriate time for ammonia capture

Taking into consideration that the objective of this experiment was to encounter the ammonia flux originating from the bed and simulate natural conditions of this emission in real time, in order to determine the appropriate ammonia adsorption period for the collector device, tests were performed lasting 1, 2, 3, 4, 12, 16, 22 and 24 hours, and for each time three repetitions were performed.

2.2.3. Location of the collector devices and collection of experimental data

Data collection was performed on three consecutive days in each week of the bird's life, between 22-28, 29-35, and 36-48 days of the productive cycle. It was taken into consideration, according to studies performed by Gates et al. (2005) and Wheleer et al. (2006), that in the first 14 days ammonia emissions are minimal and after this time emissions increase linearly.

Seeking to observe the influence of waterers and feeders on ammonia flux compared to other regions of the poultry house, four collector devices were installed in the vicinity of the feeders and four in the vicinity of the waterers (Figure 4). Ammonia flux measurements were taken during 9 days between 8:00 to 10:00 AM and 3:00 to 5:00 PM.

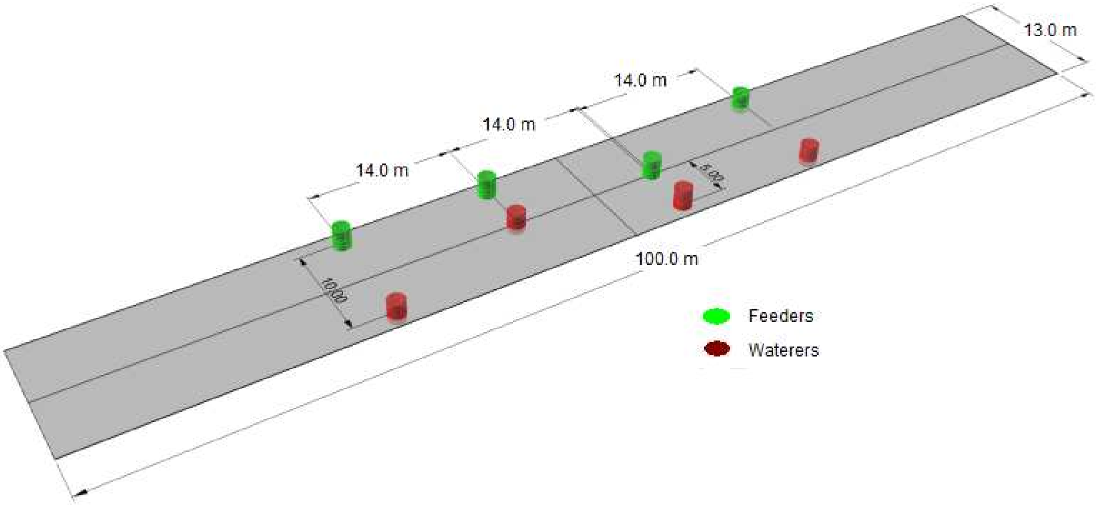

Figure 3 – Location of the collector devices in the regions of the feeders and waterers in the poultry house.

2.2.4. Determination of the quantity of ammonia captured

To capture volatilized ammonia, each sponge was impregnated with 80 ml of a solution composed of sulfuric acid (1 mol L^{-1}) and glycerine (3%), corresponding to an adaptation of the ammonia fixation method by diffusion, whose quantification is performed by acid-base titration using the Kjeldhal method (AOAC, 1970).

To extract ammonia captured in the sponge, 80 mL of a potassium chloride (KCl) solution with a concentration of 0.5 mol L^{-1} added to 40 mL of water was used. This solution mixed with the sponge was prepared in a Tecnal model TE-0363 nitrogen distillation column. After distillation, the condensed sample was titrated with hydrochloric acid (HCl) at a concentration of 0.5 mol L^{-1} (AOC, 1970).

The NH_3 concentration (g NH_3) captured by the sponge was obtained by the volume of the tilter solution (mL), the solution concentration (mol L^{-1}), and number of moles of NH_3 (17). Using equation 1, the SMDAE mass flux was obtained.

$$SMDAE \quad (g\,NH_3\,m^{-2}\,s^{-1}) = \frac{NH_3}{A\,t} \tag{1}$$

where SMDAE is NH_3 mass flux (g NH_3 m^{-2} s^{-1}); NH_3, NH_3 mass (g NH_3); A, sponge area (m^2); t, exposure time of sponge (s).

2.2.5. Determination of the efficiency of the SMDAE

To determine the efficiency of the proposed SMDAE method in terms of ammonia recovery, the difference between the quantity of NH_3 in the litter and quantity of NH_3 recovered by the sponge were determined. Ten repetitions were performed to verify this value.

2.3. The theoretical proposed SMDAE diffusion method and the mass convection method

The proposed SMDAE diffusion method is derived from Fick's Second Law. A schematic of the prototype is presented in Figure 4, where $C_{A,s}$ (g m^{-3}) corresponds to concentration of specie A at the litter bedding surface, $C_{A,\,Z}$ (g m^{-3}) concentration at height Z of the sponge; J''_A that is equal to the ammonia emission flux SMDAE captured by the sponge (g m^{-2} s^{-1}); and D_{AB} is the diffusion coefficient of ammonia in the air (0.28 x 10^{-4} m^2 s^{-1}) according to Incropera and DeWitt (1999).

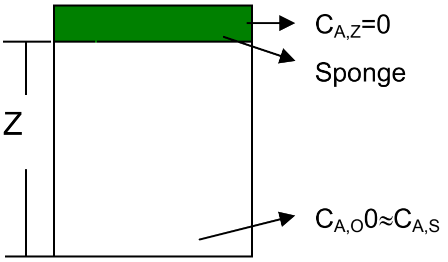

Figure 4 – Mass diffusion model of the prototype.

$$J''_A = SMDAE = -D_{AB}\frac{\partial C_A}{\partial Z} = \frac{D_{AB}(C_{A,O} - C_{A,Z})}{Z} \tag{2}$$

$$SMDAE = \frac{D_{AB}\, C_{A,S}}{Z} \tag{3}$$

For the mass convection model, a boundary limit model was used for concentration of a chemical species on a flat surface, where N''_A is the ammonia flux (g m^{-2} s^{-1}) and h_m the mass diffusion coefficient. This coefficient is a function of the Reynold's number (Re) and the Schmidt number (Sc); V is the average wind speed at the height of the birds; L is the length of the installation; and ν is the viscosity of the air. Mass flux by convection is determined as (INCROPERA; DeWITT, 1999):

$$N''_A = h_m(C_{A,S} - C_{A,\infty}) \tag{4}$$

For the case in which it is considered outside the boundary limit, mass flux is determined as:

$$N''_A = h_m\, C_{A,S} \tag{5}$$

Because flow in the building is turbulent, the mass convection coefficient is calculated as:

$$h_m = \frac{D_{AB}\ 0{,}0296\ \mathrm{Re}^{\frac{4}{5}}\ Sc^{\frac{1}{3}}}{L}$$

$$0{,}6 < Sc < 3000 \qquad (6)$$

Where

$$\mathrm{Re} = \frac{VL}{\upsilon} \qquad (7)$$

$$Sc = \frac{\upsilon}{D_{AB}} \qquad (8)$$

2.4. Statistical analyses

After the experiments, the data obtained from both measurement methods (SMDAE diffusion and convection models N''_A) were titrated and analysed statistically, and the following hypotheses were tested:

Null hypothesis (Ho): data of NH_3 flux are equal for the two methods tested.

$$SMDAE = N''_A \qquad (9)$$

Alternative hypothesis (H1): Disparity of the NH_3 concentration data between the two tested methods.

$$SMDAE \neq N''_A \qquad (10)$$

If proven that H1 is true, a linear regression analysis will be performed to determine the coefficients of the model expresed in equation 3 using the programs SAEG version 9.1 (2007) and Sigma Plot V11.0:

$$\text{SMDAE} = a\,(N''_A) + b \qquad (11)$$

where a and b are the coefficients to be obtained experimentally via the regression.

To determine the incidence of variables such as location (waterer and feeder) and the time of the day for statistical analysis, the Tukey test was used at significance levels of 1 and 5%.

A regression analysis was performed to verify correlations between ammonia flux in function of variables such as pH, litter moisture content and age of the birds using the SAEG version 9.1 program (UNIVERSIDADE FEDERAL DE VIÇOSA – UFV, 2007).

2.5. Acquisition of experimental data

Background ammonia concentration data in the environment were obtained from an electrochemical detector “Gas Alert Extreme Ammonia (NH3) Detector” from BW Technologies with a measuring range from 0-100 ppm, temperature between -4 to +40°C, relative humidity from 15% to 90% and presenting an accuracy of ± 2% (at 25ºC and RH between 5% and 95%). Data collection was performed in twenty minutes interval.

Air temperature at sample height was measured (DS1820, Dallas Semiconductor, address). Energy was provided to the 1-wire^{TM} system by a parasitic feed derived from the data transmission conductor, where only two conductors are necessary. Temperature measurements were made every five minutes.

Air speed (m s^{-1}) was measured with a digital wind gage (Testo 425), with a range between 0-20 m s^{-1}, precision of ± 0.5 (°C), accuracy of 1% (pressure) and 2.5% (m s^{-1}) and 0.1°C, positioned five centimeters in front of each sponge on the upwind side. Air velocity data collection was performed in five minutes interval.

Relative humidity of the air inside and outside of the poultry house was obtained at diverse points representing the entire poultry house, using independent systems (Hobo H8-032) with accuracy of ±0.7 at 21°C. Data collection was performed at one second intervals.

The pH of the poultry litter was determined in the laboratory using a digital pH meter, for which each sample of the bed collected in the installation was diluted in water at a 1:4 proportion (bed sample:water).

Moisture content of the litter was determined in the laboratory as the mass difference between the dry and moist mass using an oven at 105°C.

3. RESULTS AND DISCUSSION

Figure 5 presents the behavior of the ammonia mass captured by the collector device encountered by the mass diffusion method in function of the time, at the significance level of $p < 0.01$. It was observed that the behavior of the curve of ammonia for all replicates was linear in function of time, with a greater increase in emissions after the prototype was exposed for four hours. Hence, the prototypes were exposed for no more than two hours to facilitate sampling in the field and allows for a larger numbers of experimental replicates.

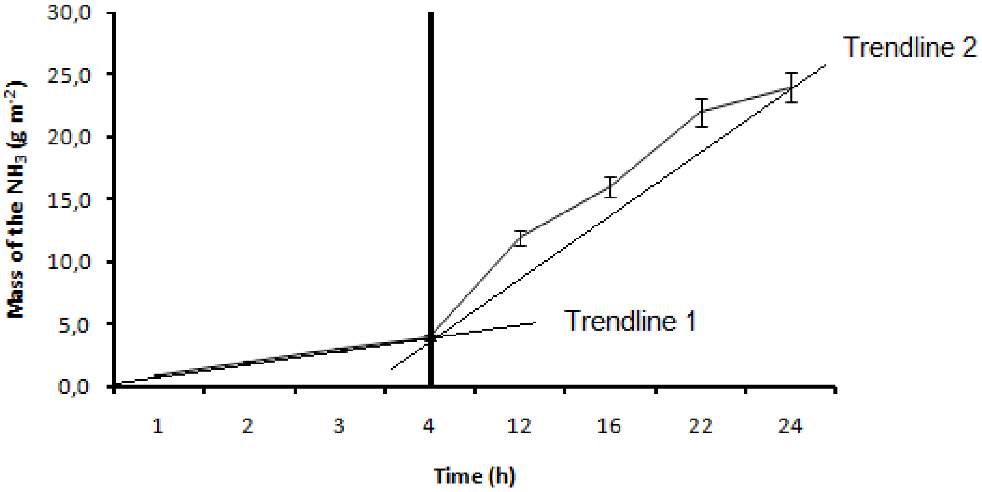

Figure 5 – Ammonia mass in function of time.

In Table 1 the ammonia mass recovery data are presented as well as the ammonia recovery curve as a function of its volatilization. The utilized collector device had a recovery efficiency of 77.55 ± 4.32 g NH_3 m^{-2}, being efficient compared with the experiments performed by Renata et al. (2001 and 2002) and Araujo et al. (2007), who encountered 70% efficiency when using the chamber collector method. Moreover, the proposed method can capture ammonia concentrations exceeding 0.5 ppm.

Table 1 – Recovery of volatilized ammonia by the collector device

Ammonia recovered by the sponge (g NH_3 m^{-2})	Ammonia volatilized from the litter (g NH_3 m^{-2})	Efficiency (%)	Minimum (g NH_3 m^{-2})	Maximum (g NH_3 m^{-2})
16.76	19.99	77.55 ± 4.32	68.85	82.47

In Figure 6, a good correlation was verified between the NH_3 quantities effectively volatilized from the litter and those recovered by the sponge, at the significance level of $p < 0.01$. Therefore, to estimate the total quantity of NH_3 recovered by the sponge, the value obtained by the equation should be multiplied by 1.2 since recovery efficiency is approximately 80%, as presented in Table 1.

After determining the efficiency of the collector device, the mass diffusion flux SMDAE was calculated by equation 3. From the SMDAE the value of $C_{A,s}$ was obtained. The ammonia fluxes were encountered using equation 4, by the mass convection model (N''_A).

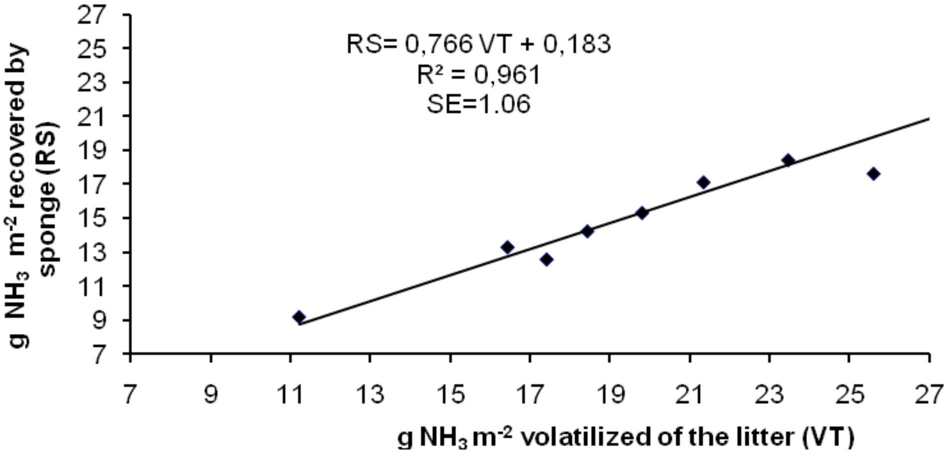

Figure 6 – Curve of ammonia recovery analyses in function of volatilization from the bed.

The mass convection coefficient (h_m) was calculated from equation 6 for turbulent flow, temperatures between 25 and 30°C, and velocities at the concentration boundary limit varying between 0.10 and 0.35 m s^{-1}, where values encountered in this experiment are in agreement with others experiment such as Brewer and Costello (1999) and Menegali et al. (2009). The value ν ranged from 15.66 x 10^{-6} and 17.82 x 10^{-6} m^2 s^{-1} (INCROPERA; DeWITT, 1999).

Values of h_m were obtained which varied between 5.15 x 10^{-4} and 1.34 x 10^{-3} m s^{-1}. These h_m values did not differ from those reported by Ni (1999) and Liu et al. (2009) who worked with velocities in this same range.

The analysis of variance between the N"$_A$ and SMDAE method was obtained and is show in Figure 7 at the significance level of $p < 0.01$. The Tukey test shows that there was a significant difference between the experimental data obtained by the SMDAE and emissions for mass convection obtained by the N"$_A$ as expected, due to the incidence of wind in the N"$_A$ method.

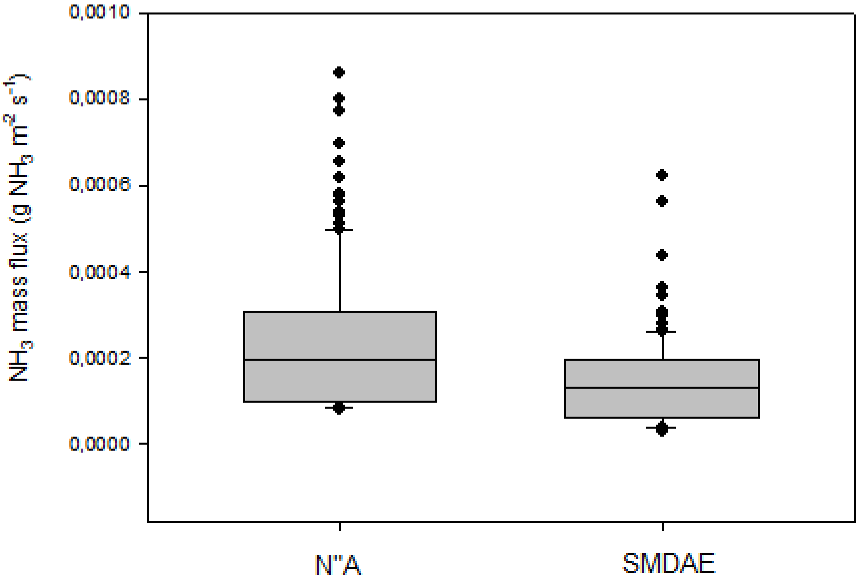

Figure 7 – Analysis of variance between ammonia flux by the N"$_A$ and SMDAE methods.

Figure 8 shows the correlation of the SMDAE model of mass diffusion and mass convection N"$_A$, at the significance level of $p < 0.01$. The values of N"$_A$ in all cases underestimate the SMDAE as is show in the Figure 7, although, it was found that the R^2 coefficient was 0.91, which means there is a high correlation between models to make use of the SMDAE method to determine N"$_A$ from poultry manure in terms of natural ventilation.

The values of N"$_A$ encountered within the range 10^{-5} and 10^{-3}gNH$_3$m^{-2}s^{-1} did not differ from those encountered by Miragliotta (2001), Redwine et al. (2002), Teye et al. (2008) and Liu et al. (2009) who worked with mass transfer methods.

In the Figures 9 and 10, the statistical analysis for correlation of the convective mass flux (N"$_A$) with variable times during the day and location of the samples (waterer and feeder) is presented. Results of the analysis of variance at the confidence level (P < 0.01) showed that both time of day and location are significant.

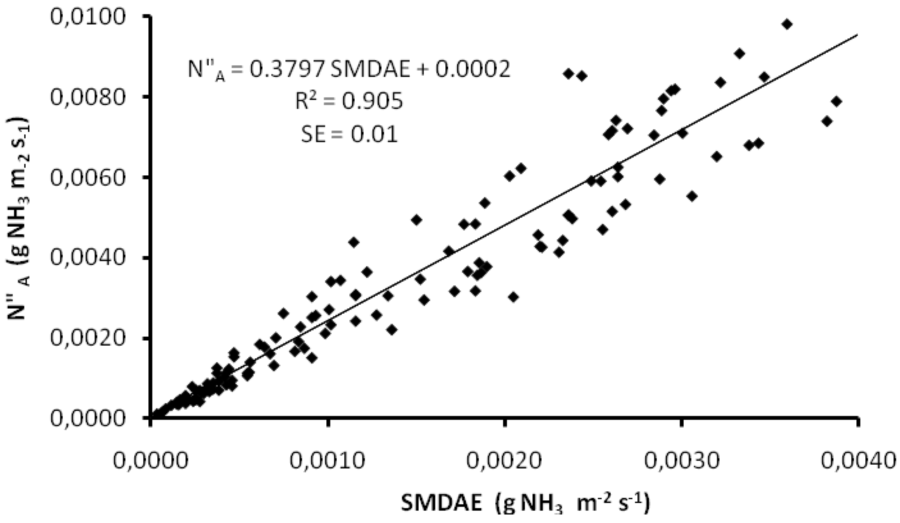

Figure 8 – Curve for analyses of the proposed mass diffusion prototype (SMDAE) and mass convection (N''_A).

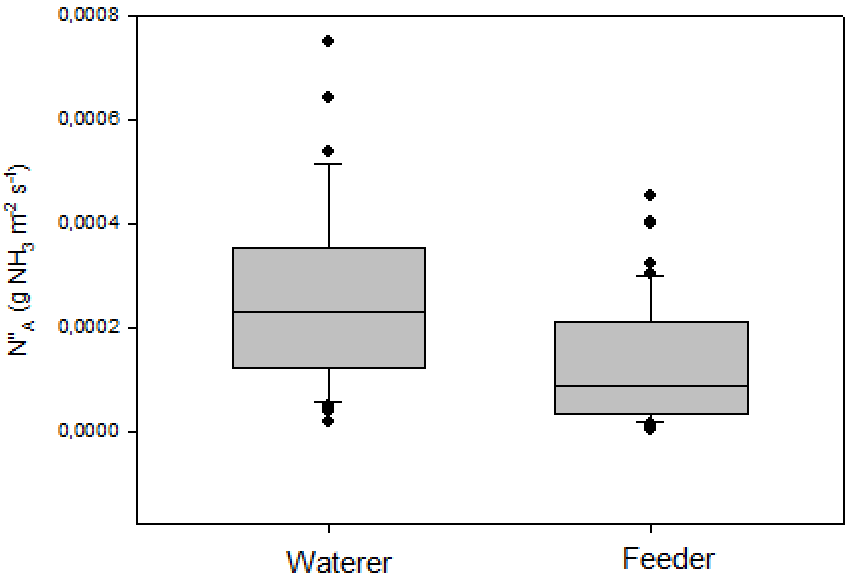

Figure 9 – Ammonia flux in function of localization.

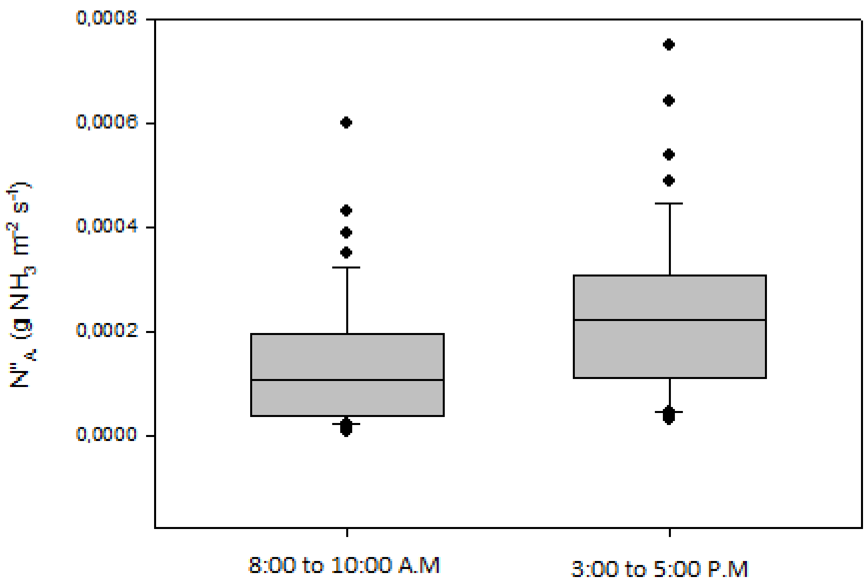

Figure 10 – Ammonia flux in function of time.

It is possible that the difference in ammonia flux (N”$_A$) from the litter in the areas of the feeders and waterers may be due to the lower moisture content near the feeders in comparison with the waterers. This was expected since according to Miragliota (2001), Jones et al. (2005) and Wheeler et al. (2008) the total volatilized ammonia (TAN) increases when the moisture of the litter bedding is elevated.

Regarding ammonia flux (N”$_A$) in function of time, the N”$_A$ is likely higher between 3:00 to 5:00 P.M than 8:00 to 10:00 A.M, because in the afternoon both the temperature inside of the poultry house and the litter increases, aiding ammonia volatilization.

Figure 11 represents the typical ammonia flux distribution by convection from the poultry litter between 8:00 to 10:00 AM and 3:00 to 5:00 PM, in an area of the litter representative of the study. A greater uniformity in ammonia flux was observed between 3:00 to 5:00 PM in relation to 8:00 to 10:00 AM, which may be due to the fact that between 8:00 to 10:00 AM the air flux over the litter is less uniform since at this time the lateral curtains of the building are opened to begin lateral ventilation, where in the afternoon they simply remain open.

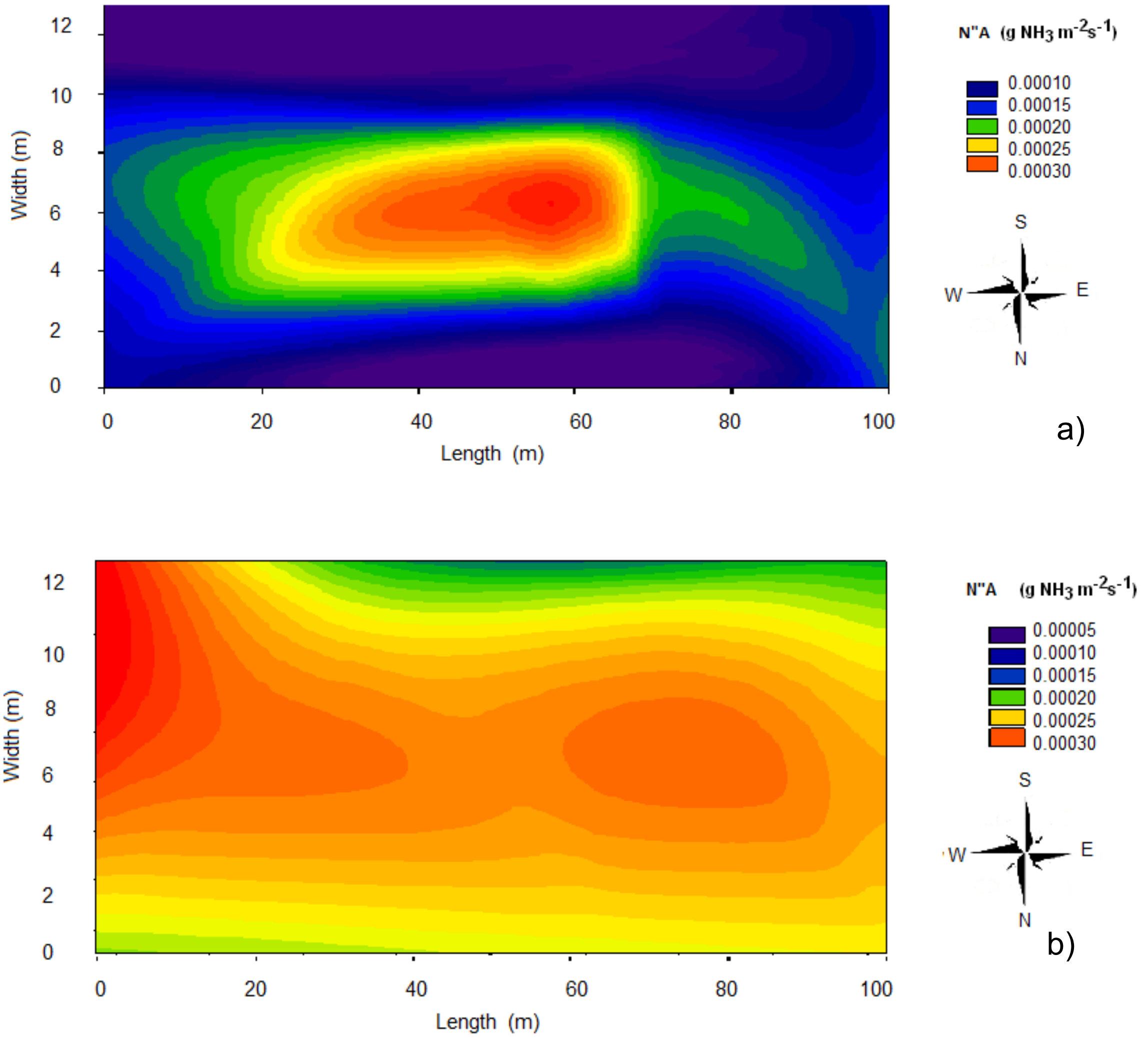

Figure 11 – Typical distribution of ammonia flux from the poultry litter at: a) 8:00 to 10:00 AM b) 3:00 to 5:00 PM.

Figure 12 represents the relationship between the ammonia flux (N”$_A$) in function of age of the birds at the significance level of $p < 0.05$. A linear increase in ammonia flux was observed between 24 days old and the age of slaughter. From the equation adjusted to the data represented in Figure 12, a tendency of the N”$_A$ behavior can be analyzed in function of the age of the birds.

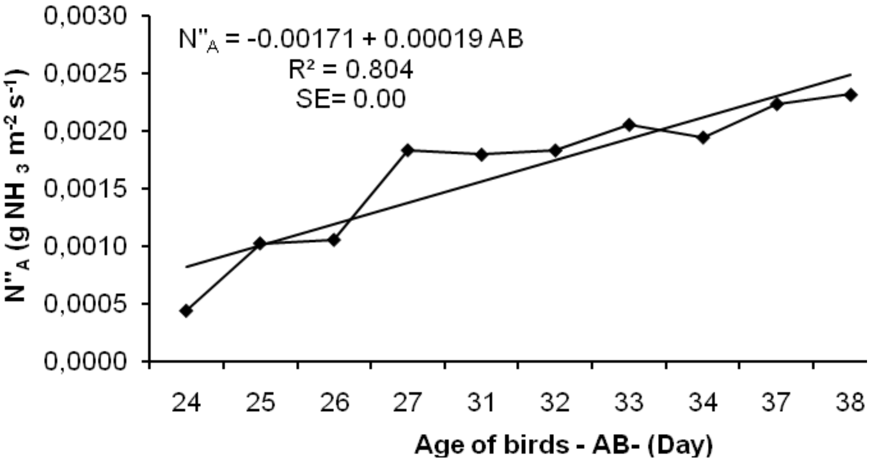

Figure 12 – Ammonia flux in function of age of the birds ($P < 0.001$).

From Figure 13 and 14 the relationship between N''_A, moisture content and pH of the bed can be observed at the significance level of $p < 0.05$. An exponential trend was also seen in both cases which permitted for inferring a statistical tendency; however it is possible to predict behavioral values of these variables in function of the ammonia flux.

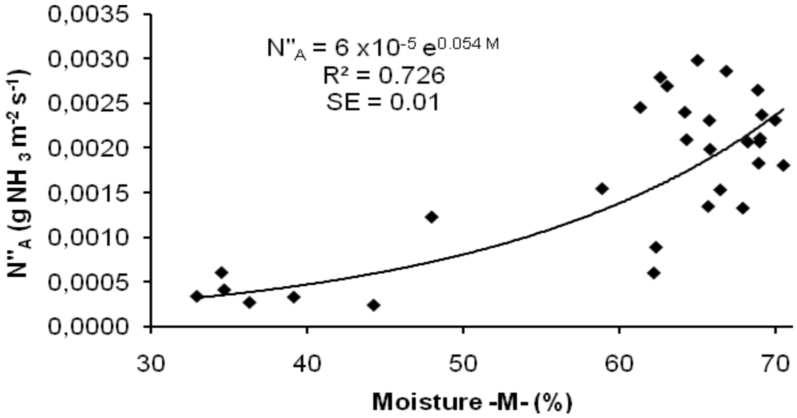

Figure 13 – Ammonia flux in function of the bedding moisture content.

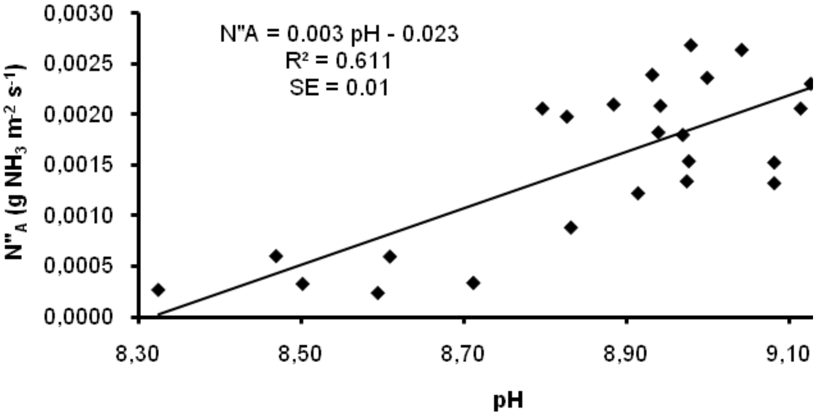

Figure 14 – Ammonia flux in function of pH.

In Figure 15 a direct relationship between ammonia emission, age of the birds and moisture content of the litter was observed, reaching maximal values when litter moisture content is greater than 50% and the birds are more than 35 days old. This aspect coincides with that of other studies performed by Osorio et al. (2009), Tinôco et al. (2004), Miragliotta (2001) and others.

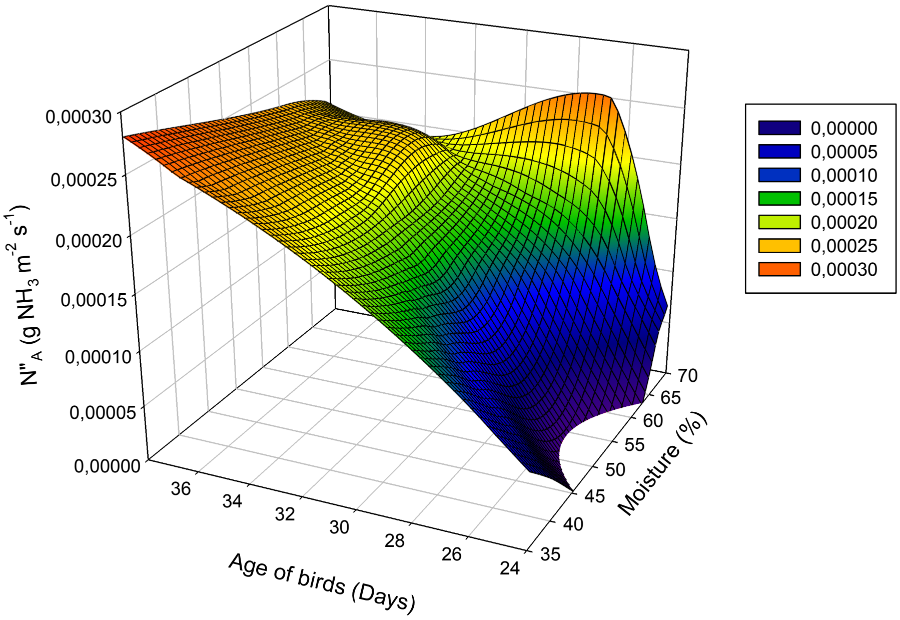

Figure 15 – Ammonia flux in function of the age of the birds and moisture content of the bed.

4. CONCLUSIONS

The proposed SMDAE mass diffusion has a good relationship with the N"$_A$ mass convection method, which is the method most commonly used when working with mass balances from ammonia sources. Therefore, the SMDAE method may be used to determine ammonia flux (N"$_A$).

The SMDAE method presented a recovery efficiency of approximately 78% of total volatilized ammonia, and can capture ammonia at concentrations as high as 0.5 ppm. It is thus indicated that the method may be considered as efficient and used as an alternative to determinate N"$_A$ inventories in installations with natural ventilation.

Although h_m has been calculated theoretically, for natural ventilation conditions with air speeds at the height of the birds varying between 0.10 and 0.35 m s^{-1}, the encountered values are not different from h_m values encountered in other studies.

The SMDAE method could be improved to be used for determination of N"$_A$ forced ventilation conditions, for which the technique must be perfected and h_m values specified for different velocity ranges, litter materials and cycles for its validation.

5. ACKNOWLEDGEMENTS

The authors would like to thank the National University of Colombia for the great opportunity, Colciencias-Colombia, the Brazilian State Government Agency FAPEMIG, the National Counsel of Technological and Scientific Development (CNPq - Brazil) and Federal ageny CAPES for their financial support and the Federal University of Viçosa (UFV-Brazil).

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CHAPTER 2

VALIDATION OF A METHODOLOGY FOR DETERMINATION OF AMMONIA FLUX GENERATED IN POULTRY HOUSES SUBMITTED TO NATURAL VENTILATION

ABSTRACT: Due to small daily and seasonal temperature ranges, in most tropical and subtropical regions the structures used in the animal production industry are predominantly open, typically relying on natural ventilation. By being open, however, it is very difficult to quantify the rate of pollutant emissions such as ammonia (NH_3). In this sense some methods have been developed to reduce this difficulty, but most are costly and complex, preventing their implementation in practice. The aim of this work was to adapt and validate the Saraz method for determination of ammonia emissions (SMDAE) reported by Osorio (2010), to determine the ammonia flux generated in poultry houses with natural ventilation. It was found that the proposed method can be used for natural ventilation conditions with wind speeds greater than 0.1 m s^{-1} and NH_3 concentrations greater than 1 ppm, and that there is a good correlation between the values determined by this method and those obtained by the characteristic equation for calculating emissions that are based on knowledge of the NH_3 concentration, air speed and temperature.
Keywords: NH_3 flux, poultry houses, natural ventilation, SMDAE method.

RESUMO: Devido à pequena amplitude térmica, própria das regiões tropicais e subtropicais, tem-se que os abrigos usados na indústria de produção animal do Brasil e de America do Sul são predominantemente abertos fazendo-se uso do acondicionamento e ventilação natural a maior parte do tempo. Por serem abertos, contudo, fica muito difícil quantificar a taxa de emissão de gases, entre os quais se destaca a amônia (NH_3). Neste sentido alguns métodos foram desenvolvidos como objetivo de sanar esta dificuldade, mais a maioria deles são onerosos e complexos, inviabilizando a sua aplicação na pratica. Com base no exposto objetivou-se com este trabalho adaptar e validar o Método

Saraz (Saraz method for determination of ammonia emissions - SMDAE), para determinar o fluxo de NH_3 emitida pelas laterais dos galpões avícolas submetidos à ventilação natural. Verificou-se que o método proposto pode ser usado com confiabilidade em condições de ventilação natural com ventos maiores que 0,1 m s^{-1} e concentrações de NH_3 maiores que 1 ppm. Encontrou-se alta relação entre os valores de fluxo de amônia encontrados pelo método proposto e aqueles obtidos na equação característica para o cálculo de emissões a qual é baseada no conhecimento da concentração de NH_3, velocidade e temperatura do ar.

Palavras-chave: Fluxo de NH_3, galpões avícolas, ventilação natural, método SMDAE.

1. INTRODUCTION

Understanding ammonia emission rates to the atmosphere is of extreme importance, not only because of the effect that this gas has on the environment in general, but also due to the direct relation that increased concentration has on the health and productivity of chickens and people.

The ammonia emission rate is estimated as the product of the gas concentration and the ventilation rate which exits through lateral openings or the exhaust fans from inside the structure at the same time, where its calculation is performed by continuous monitoring. However, although the concept is quite simple, both concentration as well as ventilation rates are difficult to accurately measure (GATES et al., 2005; GATES et al., 2008; REIDY et al., 2008).

The ammonia emission rate was calculated by Wheeler et al. (2006) as being the mass of NH_3 emitted by the poultry houses per unit of time. Some methods to measure NH_3 emissions in naturally ventilated installations with manure storage have been developed, where the most commonly utilized are those based on methods of external and internal tracer gases (PHILLIPS et al., 2000; DEMMERS et al., 2000; PHILLIPS et al., 2001; DEMMERS et al., 2001; SCHOLTENSA et al., 2004; MOSQUERA et al., 2005).

One of the most important aspects when dealing with ammonia emissions is calculation of the ventilation rate of the installation. Determination of this rate, principally in naturally ventilated buildings, can be very difficult due to the instability of this type of ventilation. In the case of Brazilian broiler houses, it is even more difficult to measure ventilation rates because strong natural air currents in the opposite direction of the fans must be considered, which generate contantly varying flow rates (XIN et al., 2003).

Thus, the methods for evaluation of ammonia emissions, such as tracer gases, continuous monitoring and mass balances offer precision and accuracy, and can be encountered in articles reported by Arogo et al. (2003), Jacobson et al. (2005), Blunden et al. (2008), Faulkner et al. (2008) and Osorio et al. (2009). However, application of these methods is more difficult in conventional broiler houses located in tropical climates due to the non-uniformity of ammonia emissions caused by the behavior of openings which generated different air flows in each exhaust point of the building.

Based on these facts, the objective of the present study was to adapt and validate the Saraz method for determining ammonia flux (Saraz method for determination of ammonia emissions-SMDAE), which is a simple and low cost method to be used for determining the rate of ammonia flux in poultry houses which are subjected to natural ventilation conditions.

2. MATERIAL AND METHODS

The present project was developed at the Department of Agricultural Engineering of the University Federal de Viçosa-Brazil, and at a conventional commercial broiler house integrated with the Pif – Paf Alimentos S/A company, located in the municipality of Vicosa, MG, Brazil.

According to the Köppen classification, the region is Cwb – high altitude tropical climate with a rainy summer and pleasant temperatures. This study was performed during the summer, with an average temperature of 22°C and relative humidity varying between 50 and 70%.

2.1. Characteristics of the confinement

The commercial poultry house utilized in this experiment presented lateral air openings which remained open during the day. A total of 14,000 Cobb broiler chickens were housed in the confinement with a density of 12 birds m^{-2}. Dimensions of the building were 100 m x 13.5 m (Length x Width) with 3 m high ceilings, 0.50 m overhang and 20° roof inclination (Figure 1).

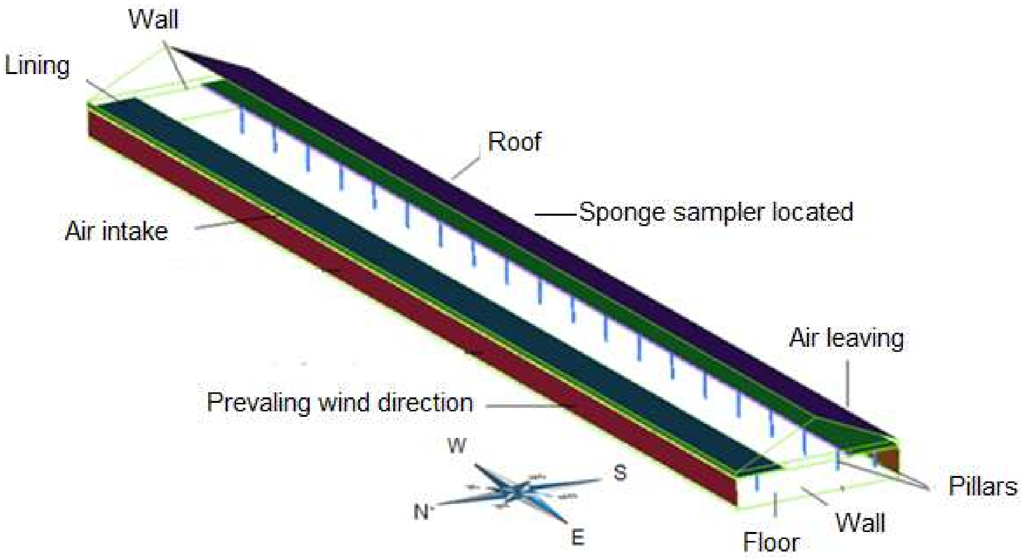

Figure 1 – Characteristics of the experimental building.

The poultry house, with minimal thermal insulation as is typical in Brazil and South America, was open during the experimental period with natural ventilation, and the bedding was composed of fresh coffee hulls.

2.2. Quantification of the ammonia flux using the Saraz method SMDAE

The operating principle of the SMDAE (Saraz method for determination of ammonia emissions - SMDAE), proposed by Osorio (2011a), was adapted for quantification of the ammonia flux of this gas which is emitted by an open, naturally ventilated poultry house.

Adaption of the SMDAE method consisted of establishing sampling points, using polyurethane sponge samplers of 20 cm in diameter each and thickness of 2 cm, forming a homogeneous mesh organized at the lateral opening of the building in the opposite direction of the predominant wind (i.e. downwind side of building).

At these equidistant points, twelve (12) polyurethane sponges were positioned along the lateral wall, near the air outlets on lines A, B, C and D, at heights of 0.80, 1.50 and 2.20 m from the floor (Figure 2).

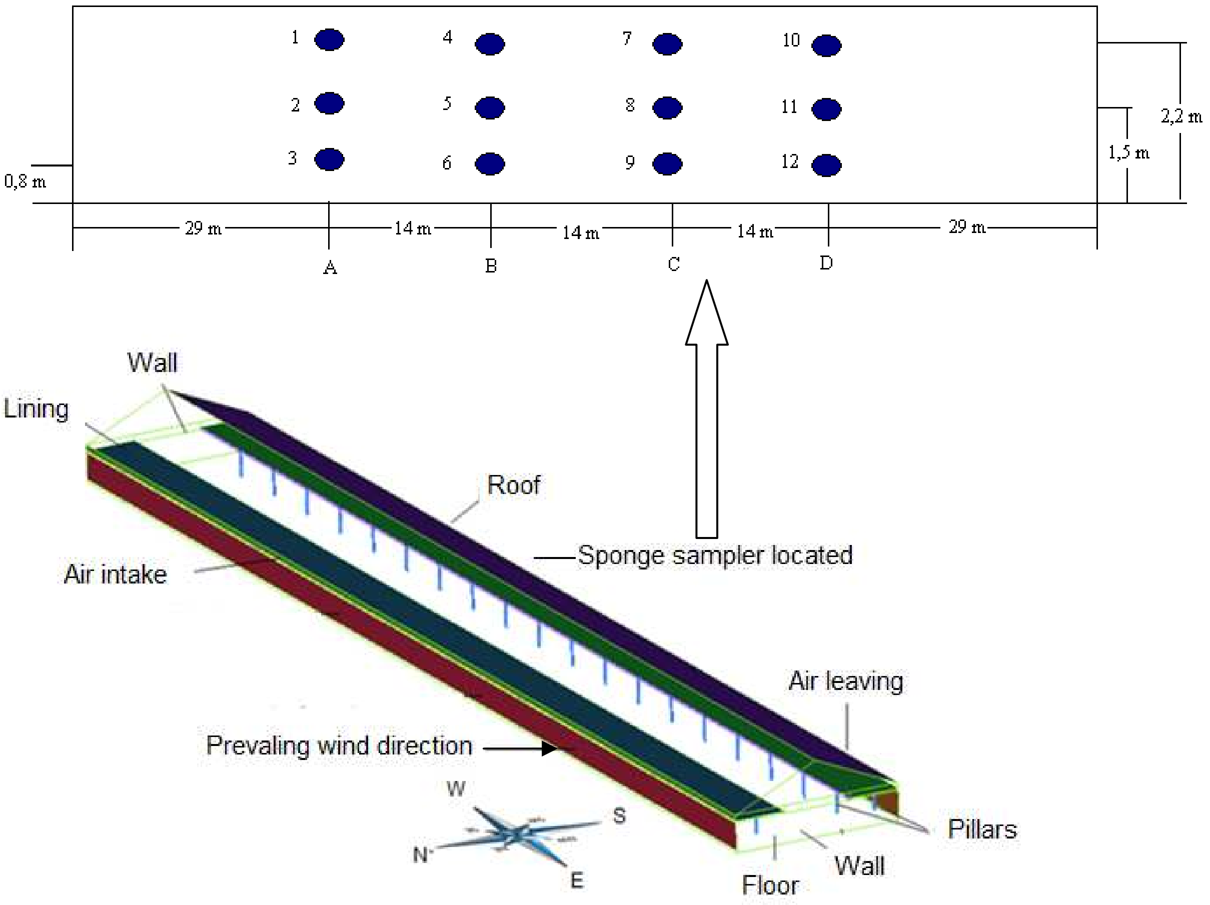

Figure 2 – Elevation view of the downwind side of poultry house showing the position of the ammonia capturing devices (sponge samplers) on the lateral wall.

A Tukey test was performed to determine if there were significant differences in the ammonia flux captured by the samplers, depending on location along the lateral opening.

2.2.1. Determination of the amount of ammonia captured by the SMDAE method

To capture volatilized ammonia, each sponge was impregnated with 80 ml of a solution composed of sulfuric acid (1 mol L^{-1}) and glycerine (3 %), corresponding to adaptation of the ammonia fixation method by diffusion, whose quantification is performed by acid-base titration using the Kjeldhal method (AOAC, 1970).

To extract ammonia captured in the sponge, an 80 mL solution of potassium chloride (KCl) with a concentration of 0.5 mol L^{-1} was added to 40 mL of water. This solution mixed with the sponge was prepared in a Tecnal model TE-0363 nitrogen distillation column. After distillation, the condensed sample was titrated with hydrochloric acid (HCl) at a concentration of 0.5 molL^{-1}.

The NH_3 concentration (g NH_3) captured in the sponge was obtained by the volume of the titrating solution (mL), the solution concentration (mol L^{-1}) and number of moles of NH_3 (17). Then, using equation 1, the SMDAE ammonia flux was obtained.

$$SMDAE \quad (g\, NH_3\, m^{-2}\, s^{-1}) = \frac{NH_3}{A\,t} \tag{1}$$

where SMDAE is Ammonia flux (g NH_3 m^{-2} s^{-1}); NH_3, NH_3 mass (g NH_3); A, sponge area (m^2); t, exposure time of the sponge (s).

2.3. Validation of the method

To validate the proposed method, the ammonia flux (NH_3 mass emitted in the poultry houses per unit time) was computed using the adjusted equation (equation 3) proposed by Wheeler et al. (2006) (equation 2).

$$ER_1 = Q_1\, M\, \left(NH_{3e} - NH_{3i}\right) 10^{-6} \frac{W_m}{V_m} \frac{T_{std}}{T_a} \frac{P_a}{P_{std}} \tag{2}$$

$$ER_2 = Q_2\, A^{-1}\left(NH_{3e} - NH_{3i}\right) 10^{-6} \frac{W_m}{V_m} \frac{T_{std}}{T_a} \frac{P_a}{P_{std}} \tag{3}$$

where ER_1 is emission rate (g NH_3 h^{-1} $bird^{-1}$); ER_2, ammonia flux (g $NH_3 m^{-2} s^{-1}$); Q_1, air flow inside the confinement, measured five centimeters in front of each sponge positioned on the upwind side, at atmospheric temperature and pressure (m^3 h^{-1} kg^{-1}); Q_2, air flow inside the confinement and immediately outside the building, at atmospheric temperature and pressure (m^3 s^{-1}); M, average body weight of the birds (kg $bird^{-1}$); NH_{3i}, NH_3 concentration of building inlet air (ppm); NH_{3e}, NH_3 concentration of building exhaust air (in this case near the internal lateral wall of the poultry house) (ppm); W_m, molar mass of NH_3 (17.031 g mole^{-1}); V_m, molar volume of NH_3 at standard temperature (0°C) and pressure (101.325 kPa), the STP (0.022414 m^3 mol^{-1}); T_{std}, standard temperature (273.15 K); T_a, absolute temperature (K); P_{std}, standard barometric pressure (101.325 kPa); P_a, atmospheric barometric pressure at the experimental site (kPa); A, area of the lateral wall (m^2).

Equation 3 was compared with the results obtained with the SMDAE method (equation 1). For this, data obtained from the two measuring methods (SMDAE and ER_2) were treated and statistically, and the following hypotheses were tested:

Null hypothesis (Ho): data of NH_3 flux are equal for the two methods tested.

$$\text{SMDAE} = ER_2 \tag{9}$$

Alternative hypothesis (H1): Disparity of the NH_3 concentration data between the two tested methods.

$$\text{SMDAE} \neq ER_2 \tag{10}$$

If proven that H1 is true, a linear regression analysis will be performed to determine the coefficients of the model expresed in equation 3 using the programs SAEG version 9.1 (2007) and Sigma Plot V11.0:

$$\text{SMDAE} = a\,(ER_2) + b \tag{11}$$

where a and b are the coefficients to be obtained experimentally via the regression.

2.4. Appropriate time for ammonia capture and gathering of experimental data

Taking into consideration that the objective was to find the ammonia flux emitted by the building, analysis of the period for sponge saturation was performed for 1, 2, 4, and 8 hours with three replications for each test.

Once defining the ideal time for exposure of the capturing sponges, it was sought to investigate if there were significant differences among different sampling locations. For this, data was collected on three consecutive days during each week of the birds lives, when they were between 22-28, 29-35 and 36-48 days old, from 8:00 to 10:00 AM and 2:00 to 4:00 PM.

The ammonia flux was not evaluated during the first weeks of the birds' lives. This is because studies completed by Gates et al. (2005) and Wheeler et al. (2006) showed that ammonia emissions in the first 21 days are minimal and according to these same authors, after this period emissions grow linearly.

2.5. Acquisition of experimental data

Air speed (m s^{-1}) was measured with a digital wind gage (Testo 425), with a range between 0-20 m s^{-1}, precision of ± 0.5 (°C), accuracy of 1% (pressure), 2.5% (m s^{-1}) and 0.1°C, positioned five centimeters in front of each sponge on the upwind side. Air velocity data collection was performed in twenty minutes intervals. The air flow Q_2 (m^3 h^{-1}) was computed by the product of air velocity and sponge area. The air direction was measurement with a weather vane.

Air temperature at the sampling height was measured (DS1820, Dallas Semiconductor). Energy was provided to the 1-wire^{TM} system by a parasitic feed derived from the data transmission conductor, where only two conductors are necessary. Temperature measurements were made every five minutes.

Background ammonia concentration data in the environment were obtained from an electrochemical detector "Gas alert Extreme Ammonia (NH3) Detector" of BW Technologies with a measuring range from 0-100 ppm, temperature between -4 to +40°C, relative humidity from 15% to 90% and presenting an accuracy of ± 2% (at 25ºC between 5% and 95% of RH). Measurements were performed at twenty minutes intervals.

Relative humidity of the air inside and outside of the poultry house was obtained at diverse points representing the entire poultry house, using independent systems (Hobo H8-032) with accuracy ±0.7 at 21°C. Data collection was performed every second.

The atmospheric barometric pressure at the experimental site was acquired by a meteorological station located nearby the experimental poultry house.

3. RESULTS AND DISCUSSION

Figure 3 shows the behavior of the ammonia flux obtained by the SMDAE method in units of hourly mass emission rate. It was observed that the sampler has the capacity to absorb volatilized ammonia that is emitted by the buildings via the lateral openings for a time greater than 8 hours since saturation did not occur. This suggests that these types of samplers can probably be used continuously during an entire day for determination of the total ammonia flux during the period in which the confinement is open.

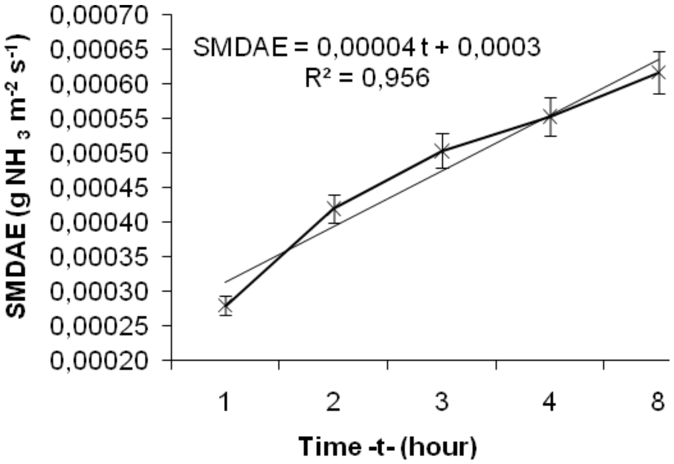

Figure 3 – Behavior of ammonia flux by the SMDAE method as a function of time.

For the objective of validating this methodology, the time utilized for ammonia gas capture was only two hours. The shorter sampling time was utilized to limit large variations in climatic factors, principally those of wind speed and direction, thus allowing for validation of the method with mass flux data obtained from the ER_2.

The analysis of variance between SMDAE and ER_2 is shown in Figure 4. The Tukey test with a significance level of $p < 0.01$ was applied, finding that there was no significant differences between the experimental data obtained by the SMDAE and that obtained by the ER_2, permitting for conclusion that the SMDAE method could be used for determination of ammonia flux coming from the lateral openings of the naturally ventilated poultry houses.

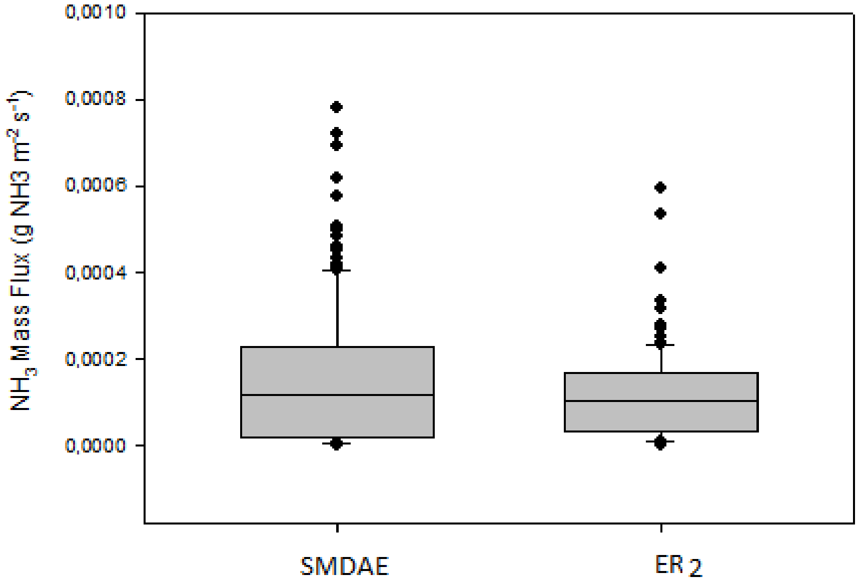

Figure 4 – Analysis of variance between the NH_3 flux determined by the SMDAE method and ER_2.

Despite the fact that there was no significant differences between the experimental data obtained by the SMDAE and the emissions obtained by the ER_2, the values obtained with SMDAE method underestimated those encountered with ER_2, and this may possibly be due to the fact that the sampler has greater capacity to obtain results in real time.

The results of ammonia flux emitted from the lateral openings of the building with SMDAE and ER_2, were found to be compatible with the ranges of values encountered in other studies, varying from 10^{-7} to 10^{-4} g NH_3 m^{-2} s^{-1} as reported by Nicholson et al. (2004), Hayes and Curran (2006), Faulkner et al. (2008), Gates et al. (2008), Liu et al. (2009) and others.

The graph illustrating the ammonia flux values determined by the SMDAE in function of the time of day are shown in Figure 5. The Tukey test ($P < 0.01$) indicated that there was significant differences between NH_3 flux determined by SMDAE method at 8:00 to 10:00 AM when compared with values obtained from 2:00 to 4:00 PM; this result may be explained by the fact that during the night the curtains are generally closed, therefore accumulated NH_3 gas concentrations in the installation are rapidly liberated when the curtains are opened.

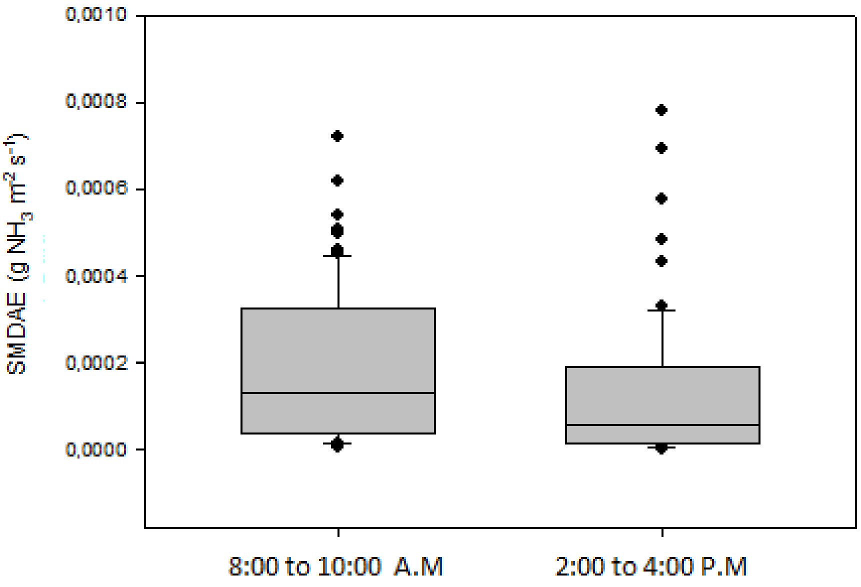

Figure 5 – Ammonia flux determined by the SMDAE method in function of the time period.

Figure 6 displays the ammonia flux values obtained by the SMDAE in function of the entrance angle of the wind measured in the lateral wall opposite to the lateral wall where the sponge samplers were located. During the experimental period two predominant wind directions were observed, referred to the angle between the wind and the building wall plane, which were 90° and 45°.

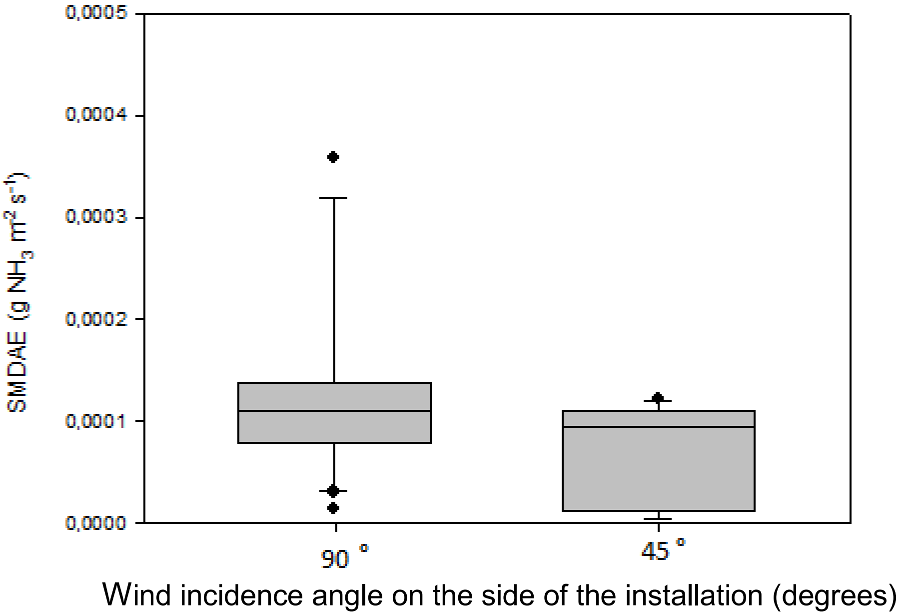

Figure 6 – Ammonia flux determined by the SMDAE method in function of angle of the wind at the lateral opening.

The Tukey test at the significance level of $p < 0.01$, indicated that there was significant differences between NH_3 flux determined by the SMDAE method with winds at 90° and 45°. It was found that when the dominant wind was at 90°, the ammonia fluxes were greater when compared to winds at 45°. According to Osório (2011b), this may be due to the fact that when the winds enter at 90° they result in greater NH_3 accumulations at the lateral exits due to the effects generated by the guard rails and building support columns.

In Figure 7 and 8 the average ammonia flux obtained with the SMDAE method as a function of sampler location and time of day are presented, at the significance level of $p < 0.01$. There were significant differences only in samplers 6, 8 and 9 located on the lateral wall in the experimental data obtained by the SMDAE in relation with the others samplers as a function of sampler localization between 8:00 to 10:00 AM. No significant differences among the samplers was observed between 2:00 to 4:00 PM.

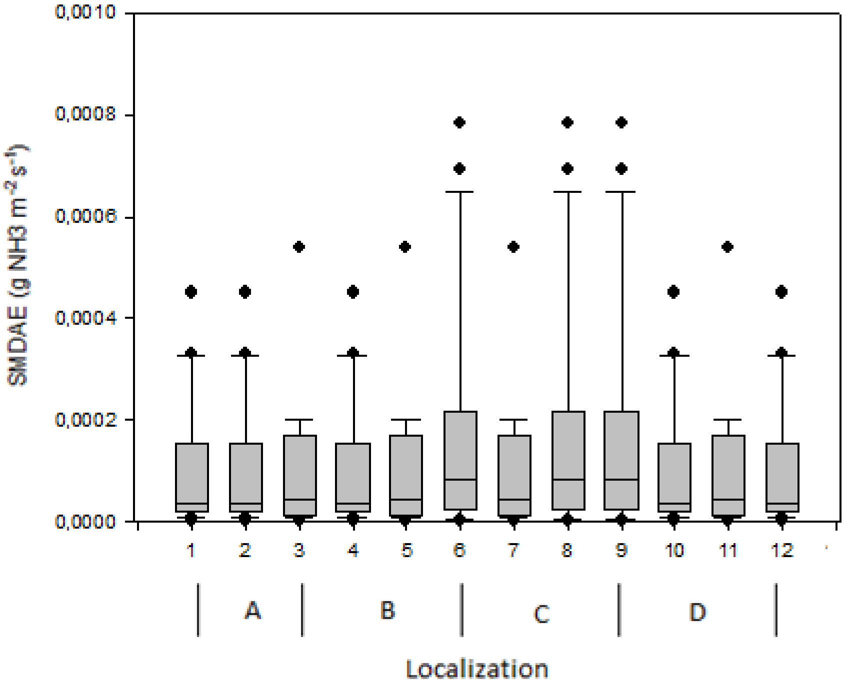

Figure 7 – Ammonia flux calculated by the SMDAE as a function of location of the samplers on the lateral wall from 8:00 to 10:00 AM.

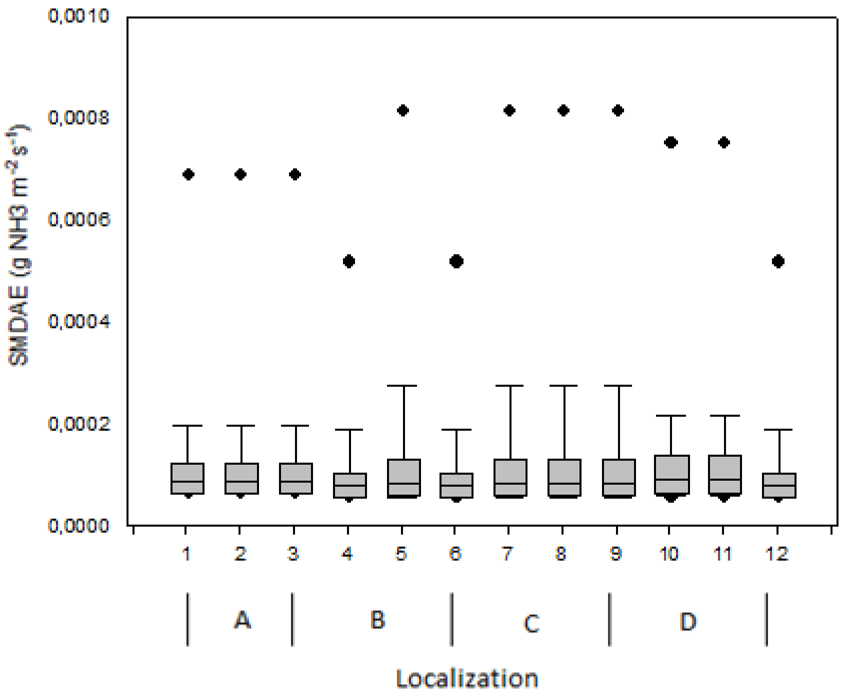

Figure 8 – Ammonia flux calculated by the SMDAE as a function of location of the samplers on the lateral wall from 2:00 to 4:00 PM.

In both situations (from 8:00 to 10:00 AM and 2:00 to 4:00 PM) the values obtained at the ends of the lateral wall on lines A and D (Figure 2) are less than lines B and C (Figure 2). This may be due to the fact that the birds generally gathered in the central regions (B and C lines) of the poultry buildings and as a consequence there is a greater concentration of manure and formation of ammonia gas, coinciding with that reported by Teye and Hautala (2008) and Tinôco et al. (2008).

Typical distribution of ammonia flux by the SMDAE method at the lateral wall where were the sampler sponges were located from 8:00 to 10:00 AM and 2:00 to 4:00 PM, are represented in Figure 9. It can be observed that between 8:00 and 10:00 AM the distribution of ammonia flux is more uniform than from 2:00 to 4:00 PM.

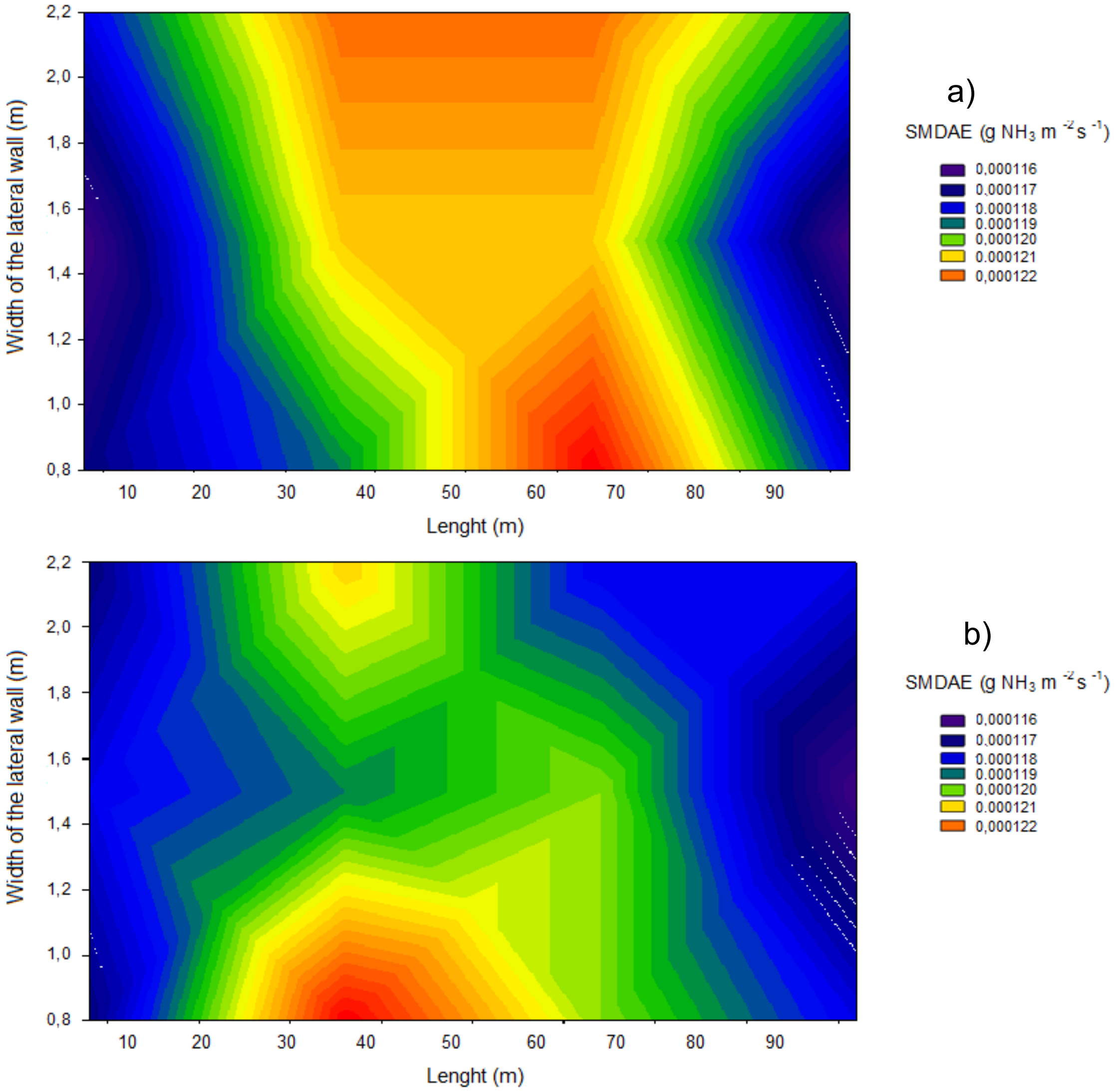

Figure 9 – Typical distribution of ammonia flux at the lateral wall: a) between 8:00 and 10:00 AM and b) between 2:00 and 4:00 PM.

This result can be explained by the fact that the curtains are opened early in the morning, and the NH_3 concentration and air velocity distribution is almost uniform in entire area for the lateral wall. In the afternoon, when the curtains have already been open for hours the air movement tends to stabilize, generating lower concentrations than in the morning.

4. CONCLUSIONS

Adaptation of the SMDAE (Saraz method for determination of ammonia emissions) presented good behavior and could be an alternative for determining ammonia flux emitted by the lateral openings of the poultry houses submitted to natural ventilation.

The proposed method may be used in conditions of natural ventilation with wind speeds greater than 0.1 m s^{-1} and NH_3 concentrations greater than 1 ppm, which are the minimum values registered in these conditions. Although the SMDAE method is less precise than other methods such as continuous monitoring with external and internal tracer gases, it may be a viable and reliable alternative due to its simplicity of application and low cost.

No differences were encountered in ammonia flux at the twelve points located at the lateral openings along the length of the upwind side of the building, suggesting that future studies should continue placing samplers at the minimal twelve points used in this study due to climatologic variability of the location characteristics of subtropical and tropical climates where the wind changes direction frequently.

5. ACKNOWLEDGEMENTS

The authors would like to thank the National University of Colombia for the great opportunity, Colciencias-Colombia, the Brazilian State Government Agency FAPEMIG, the National Counsel of Technological and Scientific Development (CNPq - Brazil) and Federal agency CAPES for their financial support, as well as the Federal University of Viçosa (UFV-Brazil).

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CHAPTER 3

EVALUATION OF DIFFERENT METHODS FOR DETERMINING AMMONIA EMISSIONS IN POULTRY BUILDINGS AND THEIR APPLICABILITY TO OPEN FACILITIES

ABSTRACT: In regions of tropical and subtropical climates, as in the case of Brazil, basically all installations used for intensive broiler chicken production and other animals of economic interest operate as curtain-sided open structures with assisted mechanical ventilation. The lack of ventilation control in these facilities, as well as wind direction and velocity effects on ventilation uniformity, complicates calculation of the quantity of gasses (ammonia and others) generated by this activity during a given moment. This fact constitutes a difficulty in the evaluation of the polluting potential occurring in these open environments, as well as comparison with data encountered in closed environment facilities used in temperate climates. All developed countries of Europe and North America already possess methodologies to determine gas emissions in closed installations used in these regions. Therefore, the objective of the present study was to evaluate some specific methodologies used for determining ammonia emissions in broiler houses located in countries of Europe and the United States, and verify the possibility for application of these methodologies to open structures common in Brazil and other countries of South America. A quantitative evaluation showed that the methods with greatest characteristics of adaptability to the operational conditions and the different types of conditioned environments of buildings with positive pressure or natural ventilation systems are the methods of internal tracer gas and the portable monitoring unit (PMU) and mobile air emissions monitoring unit (MAEMU) methods. Model-based approach that uses mass balance and those of passive diffusion such as the “Ferm Tube” and Saraz Method for Determination of Ammonia Emissions (SMDAE) proposed by Osorio (2010), can also be adapted to different operational conditions of open buildings.

Keywords: Methods of ammonia emissions, air pollution, animal production, air quality, ventilation.

RESUMO: Em regiões de climas tropicais e subtropicais, como é o caso do Brasil, basicamente todas as instalações usadas na produção intensiva de frangos de corte e de outros animais de interesse econômico trabalham a maior parte do tempo abertas e com ventilação forçada. A falta de controle sobre a massa de ar renovada a cada intervalo de tempo, bem como da velocidade e uniformidade do ar da ventilação dificulta muito o cálculo da quantidade de gases (amônia e outros) gerados pela atividade em um determinado momento. Este fato constitui uma dificuldade na avaliação do potencial poluente ocorrido nestes ambientes abertos, bem como na comparação com os dados encontrados nos alojamentos fechados praticados em climas temperados, já que todos os países desenvolvidos de Europa e America do Norte já dispõem de metodologias para determinar o valor de emissão de gases nas instalações fechadas praticadas nestes tipos de regiões. Sendo assim, buscou-se com a presente pesquisa analisar algumas metodologias usadas para a determinação de taxas de emissões de amônia em galpões fechados de frangos de corte, em países da Europa e nos Estados Unidos de America (USA), e verificar a possibilidade de aplicabilidade destas através da sua adaptação e emprego em estruturas abertas típicas do Brasil e de outros países de America do Sul. Uma avaliação quantitativa mostrou que os métodos com maiores características de adaptabilidade as condições de operação e aos diferentes tipos de acondicionamento ambiente de galpões com sistemas de ventilação de pressão positiva ou com ventilação natural, são o método de traçado de gases interno e o de Unidades de Monitoramento Contínuo como as unidades portáteis de monitoramento (PMU) e unidades de monitoramento moveis para emissões ao ar (MAEMU). Métodos tais como o método que usa balanços de massas e aqueles de difusão passiva como o “Ferm Tube” e o método saraz para determinação de emissões de amônia (Saraz method for determination of ammonia emissions - SMDAE) proposto por Osorio (2010), indicam também poderem ser adaptados para as diferentes condições de operacionalidade dos galpões abertos.

Palavras-chave: Métodos de emissões de amônia, poluição aérea, produção animal, qualidade do ar, ventilação.

1. INTRODUCTION

Understanding and control of ammonia emissions to the atmosphere are very important, due to its ecological effects when deposited in soils and by its direct relation with NH_3 concentrations which has a negative effect on health and productivity of animals and people (FAULKNER et al., 2008; TINÔCO et al., 2008; OSÓRIO et al., 2009).

In general, ammonia emissions generated in a closed livestock confinement have been evaluated by NH_3 concentrations exhaust fans responsible for air exchange within the installation. However, despite this being a simple concept, both measured concentrations and ventilation rates are difficult to precisely quantify in poultry buildings (GATES et al., 2005; WHEELER et al., 2006; GATES et al., 2008).

Therefore, in the case of open installations as are often encountered in Brazil, quantification of ammonia emission becomes extremely more complex. One of the aspects of greatest importance in regards to ammonia emissions is calculation of the ventilation rate in the installation. Determination of this value in naturally ventilated buildings, as well as in curtain-sided housing with mechanical ventilation, can be complicated by its instability and variability, the last considering strong opposing natural air currents contrary to flow of the fans, generating different flow rates at each moment (XIN et al., 2003).

Although there are instruments to directly measure air speed in various directions like 3-D Doppler/Ultrasonic sensing technologies, however, they are expensive and only measure at a point, not over an area, and due to these buildings are very big, so it would be very expensive to do it. For that techniques have been developed such as that used by Lee et al. (2007) which consists of a particle image velocimetry (PIV) system to simulate real conditions of air behavior.

There is also the trace gas method (DEMMERS et al., 2001; SNELL et al., 2003) which helps to obtain a precise understanding of the air velocity distribution inside installations; however calculation of the ventilation rate is still an extremely complex calculation.

General methods used to determine ammonia emissions available to date for closed installations present reasonable accuracy as reported by Phillips et al. (2001), Sun et al. (2002), Arogo et al. (2003), Gates et al. (2005), Gates et al. (2008), Blunden et al. (2008), Reidy et al. (2009) and Osorio et al. (2009). However, application of these methods is very difficult in conventional poultry buildings, principally due to the need to adapt to various operating conditions within the installations.

Based on these facts, a study was performed in which the principal methods for determination of ammonia emission used by different researchers in Europe and the USA (and which may have potential to be used in open poultry installations located in tropical climates) were evaluated in function of parameters including: cost, acquisition of data for computational numeric models, precision of data acquisition, efficiency of operation in conventional structures, efficiency of natural ventilation and positive or negative forced ventilation systems.

2. MATERIAL AND METHODS

In this study a methodology was applied for qualitative and quantitative evaluation of the principal methods available for determining ammonia emissions emitted by poultry houses, which were chosen based on primary and secondary information. Evaluation of each of the studied methods was performed based on all positive and negative characteristics for each, weighting each of these items between 0 and 10, where 0 signifies no condition for use, 1-3 poor, 4-6 regular, 7-9 good, and 10 excellent.

The evaluated characteristics of each methodology were: I. application costs; II. accuracy of data acquisition; III. acquisition of data that can be modeled; IV. operating efficiency in systems with natural ventilation; V. operating efficiency with negative pressure mechanical ventilation; VI. operating efficiency with positive pressure mechanical ventilation.

3. DETERMINATION OF NH_3 CONCENTRATION AND AIR VELOCITY DISTRIBUTIONS

Among the most utilized methods available to determine ammonia emissions in closed poultry structures, seven were selected as the most applicable for Brazil and evaluated, highlighting the advantages and disadvantages of each. They are: Model-based approach that uses mass balance, tracer gas external and internal, the passive diffusion method proposed by Osorio et al. (2010), “Ferm Tube” passive flow method, the portable monitoring unit (PMU) and mobile air emissions monitoring unit (MAEMU) Method and Dekock method (DEKOCK et al., 2009).

3.1. Tracer gas ratio technique - TGRT

The tracer ratio technique consists of establishing a similitude where the emission rate and concentration of a gas with chemical and physical characteristics similar to ammonia, denominated the “tracer gas”, and that of the species under investigation is the same at the same point and same time instant (Equation 1) (SHOLTENS et al., 2004). Carbon monoxide (CO) has been used as a tracer by Demmers et al. (1998), Demmers et al. (2001) and Scholtensa et al. (2004), which provides the advantage of being strongly absorbed by infrared sensors and its concentration is easily monitored since it has roughly the same density of air.

However, sulfur hexafluoride (SF_6) is a most amply used tracer and its concentration can be measured by gas chromatography (PHILIPS et al., 2001). Nevertheless CO_2 is also used with good results, agree some studies such as Xin et al. (2009).

$$\frac{Emission\,of\;NH_3}{Concentration\;\;of\;\;NH_3}=\frac{Emission\;\;of\;\;tracer}{Concentration\;\;of\;tracer} \tag{1}$$

The tracer gas ratio technique can be performed externally (under the influence of dominating winds) or inside the building (not depending on a particular wind direction). In both cases it is necessary to precisely know the location of all NH_3 emitting sources and distribution of the concentrations.

For typically poultry buildings in tropical climates, where the structures are generally located in the east-west direction, and both the predominant winds and lateral openings of the buildings are in the north-south direction, the TGRT both externally and internally, can be used depending on the operational conditions since the air flow that enters and exits the building does not always present uniform conditions along its length. Therefore it is necessary to understand the true distribution of wind velocities as a function of the predominant winds and the positive pressure (inlet fans) or negative pressure (exhaust fans) mechanical ventilation.

For buildings with positive or negative pressure ventilation, and either open or closed structure, the external tracer gas ratio technique can be recommended, seeking to perform measurements near the perimeter of the structure and facing the predominant winds.

In the case of open structures with natural ventilation, with no continuous predominant winds or uniform velocities, the internal tracer gas ratio technique was shown to be the most suitable for determining ammonia emissions (DEMMERS et al., 1998; DEMMERS et al., 2001). Data acquisition should be done near the perimeter of the structure since, according to Phillips et al. (2000) and Dore et al. (2004), the internal method is less susceptible to changes in wind direction than the external.

To measure the ammonia concentration in the case of the external TGRT, the process most commonly recommended is the AMANDA system (ammonia measurement by annular denuder sampling with on-line analysis), which consists of passing the air through a rotational denuder system with its walls coated with $NaHSO_4$. The gaseous mixture is transported through a conductivity detector which indicates capture of ammonia ions and has the advantage of directly measuring the air flow rate through the sensor. This method has an excellent efficiency in terms of precision, being capable of detecting ammonia at low concentrations (0.001 ppb). However in terms of cost, the AMANDA system may be the most costly (SHOLTENS et al., 2004).

When utilizing the internal TGRT, a device such as the NO analyzer is used, associated with a NH_3 catalytic converter. However this methodology requires significant experience for its management in order for reliable determination of ammonia concentration. In regards to cost, Sholtens et al. (2004) and Mosquera et al. (2005) state that the investment is large due to the required technology.

3.2. PMUs and MAEMUs methods

This method consists of determining ammonia emissions with instruments for continuous monitoring of low and medium concentrations. These devices are portable and easily encountered on the market, such as the photoacoustic analyzer and the Innova Tech Instrument, and have been utilized in studies conducted by Xin et al. (2003), Gates et al. (2007), Kim et al. (2008), Blunden et al. (2008), and Sommer et al. (2009).

Based on the necessity for continuous monitoring of ammonia in broiler houses and the difficulty of acquiring precise instruments due to their elevated costs, Xin et al. (2003) and Gates et al. (2005) developed a device denoted as the portable monitoring unit (PMUs). This device presented lower costs than high precision thermal oxidation monitors (chemifluorescence) and photoacoustic sensors which were used in the studies performed by Wheeler et al. (2006).

Amaral et al. (2007 and 2008) performed studies aiming to evaluate the efficiency of the PMUs for continuous monitoring in commercial poultry buildings in the United States equipped with negative pressure tunnel ventilation systems. The authors made comparisons between the concentration and emission of ammonia obtained by a mobile air emissions monitoring unit (MAEMUs) (Burns et al., 2007 and 2006abc) which is a reliable reference unit and corresponds to a trailer where the instruments necessary for ammonia gas emission monitoring are located. Amaral et al. (2008) determined that ammonia concentration and emission data obtained by the PMUs and the MAEMUs present significant statistical differences, and one reason for that was the sequencing of sampled ventilation rate and measured concentration – if these line up there is still a difference, but it can be adjusted.

All these methods must have instruments, besides ammonia concentration detectors, to continuously measure temperature, atmospheric pressure, and ventilation rate to obtain the emissions generated by the installations. This is initially a disadvantage due to the initial investment costs, but the major advantage is its greater accuracy.

These methods have been principally employed in closed structures which operate under negative pressure mechanical ventilation, however they can also be adapted to open structures which operate under negative or positive pressure.

It is understood that these methods can also be utilized for the case of confinements with natural ventilation; therefore, in open structures there should be a greater number of monitoring points inside the structure and near the air outlets, as well as constant monitoring of wind speed and direction along the perimeter of the structure. However this adaption may make this method complex and unfeasible due to the number instruments required.

3.3. Dekock method

This Intermittent method has been utilized by Vranken et al. (2004) and was later improved by Dekock et al. (2009) in closed hog confinements with negative pressure ventilation, in which gasses are removed via a chimney. In this system, the installations are dotted by equipment for measurements of concentration and ventilation rate at any given instant, intermittently.

Compared to methods which continuously measure ammonia emissions, this is more low-cost option. The method improved by Dekock et al. (2009) has a linear model which correlates ammonia concentration with other variables, such as external temperature, ventilation rate and animal weight (Equation 2).

Validation of the model was done by comparing the results with those obtained by continuous ammonia analyzing devices, only four times per day at any time, and maximum errors were limited to 10%, when is compared when measurements during whole day.

$$C_{NH3} = a + bV + cW + dT_i + eT_o \tag{2}$$

where C_{NH3} is concentration of ammonia in ppm; a, b, c, d, estimated coefficients; V, ventilation rate ($m^3\ h^{-1}$); W, average weight of the animals (kg); T_i, internal temperature (°C); T_o, external temperature (°C).

It is therefore understood that this method can also be used in open installations equipped with positive or negative tunnel ventilation in tropical climates when the ventilation system is operating with the lateral curtains closed. However, it is necessary to adapt a statistical understanding of emission behavior to its conditions during the entire year in order to reduce the number of experiments necessary. It initially appears that this method is not easily applied for natural ventilation systems with large lateral openings.

3.4. Passive flux methods

3.4.1. Ferm tube (passive flux samplers)

Determination of ammonia flow distributions, just as air displacement speeds, has been done by chemical methods or directly using sensors. In these categories, direct ammonia flow can be monitored by passive flux samplers, whose principle consists of using a tube in the direction of the air flow within which some acid absorbents are deposited which work to capture any amount of ammonia present in the studied flow.

According to Phillips et al. (2001), the first passive flux sampler was developed by Ferm (1986) and reported by Shorring et al. (1992), denominated the “Ferm Tube”. This method has been reported by Dore et al. (2004) and Mosquera et al. (2005), and has mainly been applied to determine ammonia emissions in cattle confinements.

In the case of poultry houses, which work either with positive or negative pressure, open or closed, this method can be used with good accuracy since they have direct air fluxes exiting the structure. However, when this type of structure operates with only natural ventilation, the samplers should be maintained in the environment under study for as long as possible since many times there is not a single wind direction and the wind speeds can be low, which may cause errors in the obtained emission values.

Cost may be high when using this method, depending on the number of samples required, and also because sampling time is in hours which does not allow easy correlation with other independent variables to obtain statistical models.

3.4.2. SMDAE method proposed by Osorio (2011)

The Saraz method for determination of ammonia emissions (Saraz method for determination of ammonia emissions-SMDAE) proposed by Osorio (2011), is a passive diffusion collector, designed based on a tubular collector located in the parts of the installation where air flux between the building and the exterior can be identified. Inside the device a collector is inserted (polyurethane sponge) whose function is to absorb the ammonia gas emitted by the building. Thus, each sponge is impregnated with a solution composed of sulfuric acid and glycerin, establishing a method for ammonia fixation by microdiffusion. It is then quantified by acid – base titration, using the Kjeldhal method (ASSOCIATION OF OFFICIAL ANALYTICAL CHEMISTS – AOAC, 1970).

For open or closed installations which operate with positive or negative pressure, and therefore when the curtains are closed, these buildings present a predominant air flux direction with good results.

When dealing with structures with lateral openings and only natural ventilation, to quantify ammonia emissions it is necessary to place the prototype simultaneously both sides, for a time period greater than two hours. This results in a greater number of samples and thus higher cost. Nevertheless, because this methodology scans a greater area for gas capture and by the simplicity of the collector, it is less onerous than the “Ferm Tube”.

One of the limitations is that this method operates best for broiler chickens older than 14 days, when the quantity of manure can cause greater ammonia production. This is because one of the disadvantages of the system is that it can only accurately evaluate ammonia conditions when concentrations are greater than 1 ppm, and this concentration is rarely reached during the first two weeks, unless the bedding is reused. Therefore, according to Osorio (2011), this method can be further improved in order to be viable at ammonia concentrations less than 1 ppm.

3.5. Model-based approach that uses mass balance

The mass balance method takes into consideration all forms of nitrogen inside a structure, generated by animal urine and manure which are deposited on the beds. To apply this method a mass balance is performed in which clear understanding is necessary of the relationship of the feed characteristics, quantity of urine and feces produced by the animal, as well as the $NH_3 – N$ fraction present in the total ammonia nitrogen (TAN) of the manure.

To determine ammonia emissions using this method, Monteny et al. (2002), Welford et al. (2003), Keener et al. (2008) and Teye et al. (2008)

generated mathematical models based on general mass transfer equations, thus developing empirical equations to determine the convective coefficient of mass transfer for different flows and geometric surfaces.

For animal production in tropical countries, where different types of poultry bedding are used and often times it is common to reuse this bedding, as well as combinations of management systems using natural and mechanical ventilation with open and closed systems, it is very difficult to employ a single mathematical model for this variety of operational conditions. Therefore it would be necessary to generate mathematical models for each condition, where the greatest difficulty would be encountering the convective coefficient of mass transfer, which is an important parameter for emissions determination.

Implementation of this methodology in terms of cost is not very high in comparison with the previously described methods. Similarly, the procedures to obtain the parameters required for the model are not difficult to acquire, however required qualified personnel are required at the site for data collection during the experimental period.

4. QUANTITATIVE ANALYSIS OF THE METHODS

Table 1 and Figure 1 present a quantitative qualification of the possibilities for use of the ammonia determination methods practiced in closed installations, with respect to their applicability in open or partially open structures typical of animal production in tropical or subtropical climates, as in the case of Brazil and other South American countries.

It was observed that, of the evaluated methods, the system of internal tracer gas and PMUs and MAEMUs methods were the most qualified methods, followed by methods the external tracing gasses method, the passive methods of the “Ferm Tube” and SMDAE proposed by Osorio (2010), had nearly the same quantitative evaluation, while the Dekock Method and model-based approach that uses mass balance had lower qualifications.

Table 1 - Quantitative qualification of some methods for measuring ammonia emissions from animal production installations

	Characteristics	Determination of the NH_3 concentration and air speed distributions			Passive diffusion and passive flux			Model-based approach that uses mass balance
		Method of external tracer gas	Method of internal tracer gas	PMU and MAEMU Methods	Dekock Method	SMDAE method proposed by Osório (2011)	Ferm Tube "Passive flux"	
I	Cost of method application in systems with positive pressure mechanical ventilation	5	5	5	5	7	6	6
II	Cost of method application in systems with negative pressure mechanical ventilation	5	5	5	5	7	6	6
III	Costs of method application in systems with natural ventilation	4	5	3	3	6	4	6
IV	Precision for obtaining data in systems with negative pressure mechanical ventilation	8	8	8	8	6	7	6
V	Precision for obtaining data in systems with positive pressure mechanical ventilation	8	8	8	8	6	7	6
VI	Precision for obtaining data in systems with natural ventilation	4	7	7	4	6	5	5
VII	Obtainment of data which can be modeled computationally or numerically	8	8	8	8	7	8	8
VIII	Operational efficiency in systems with natural ventilation	5	8	6	5	6	5	6
IX	Operational efficiency in systems with negative pressure mechanical ventilation	9	8	9	9	7	9	7
X	Operational efficiency in systems with positive pressure mechanical ventilation	9	8	9	8	8	9	7
Total		65	70	68	63	66	66	63

0 no condition for use, 1-3 poor; 4-6 regular; 7-9 good; 10 excellent.

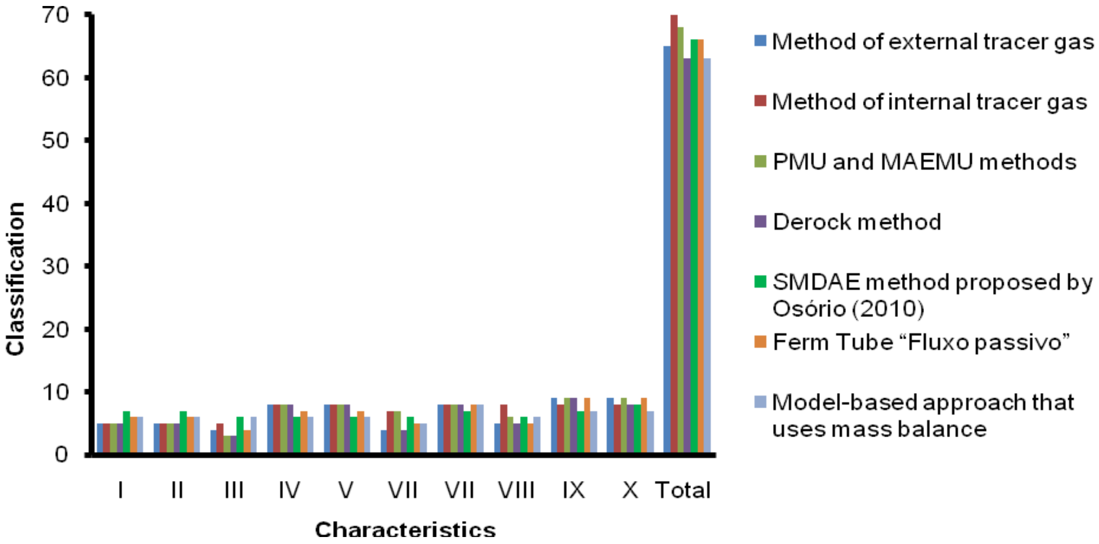

Figure 1 – Quantitative qualification of some methods for ammonia measurement.

From Table 1 and Figure 1 it can be verified that the internal tracer gas method was classified as having the greatest potential in an integral evaluation. It was also verified that the internal tracer gas method was better than the external tracer method in open and closed structures with natural ventilation and positive or negative pressure, or under different situations. The greatest disadvantage of this method is its high cost; however the greatest advantage is its accuracy.

The method for determining NH_3 concentration and air speed distributions, such as those used by Gates et al. (2007) and Blundem et al. (2008), and that developed by Xin et al. (2003) like the PMUs and MAEMUs, can also be used with good accuracy. However it can be observed that the greatest disadvantages for the MAEMUs opposite to the PMUs, are is the high initial costs since various monitoring points along the perimeter of the structure are necessary, especially in the case of natural ventilation. After compensating for the initial costs, with the system already in operation, the effect of costs evaluated in Table 1 can improve, making it possible to apply this method in tropical climates for installations with different operational forms.

Passive diffusion methods such as the “Ferm Tube” and SMDAE showed slightly poorer qualifications compared to continuous monitoring and internal tracing gasses, principally due to the fact that these methods have greater accuracies when ammonia concentrations are high (> 0.5 ppm). However, their applicability in poultry buildings with positive and negative ventilation, and natural ventilation can be applied with greater reliability, given the operational conditions of these buildings. In the case of natural ventilation, the passive diffusion methods of the “Ferm Tube” and SMDAE can be as accurate as internal tracing gasses once the birds are more than 14 days old according to Osorio (2011). However, more sampling points are required due to fluctuation of wind direction which generates an increase in costs due to the greater number of laboratory analyses necessary.

The principal disadvantage of the passive flux methods analyzed here is the fact that they do not allow continuous monitoring of emissions, as well as the exposure time depending on wind speed and direction conditions.

The external tracer gas method functions well with negative and positive pressure systems with predominant winds, however, when dealing with natural ventilation with winds in various directions and different speeds, this method may not present good reliability. Costs of this method can also be quite high, making qualification of this method poor compared to the others.

The Dekock method, despite its good accuracy, presented disadvantages such as its difficulty for use in open installations, as well as difficulties for statistical adaption to each region and condition to be used; these facts reduce its qualification.

The model-based approach that uses mass balance can be good to predict ammonia emissions generated in an animal confinement, for both conditions of natural ventilation and positive or negative mechanical ventilation. The principal disadvantage of this method is the difficulty to find the mass transfer coefficient, especially under conditions of natural ventilation, where predominant winds vary in terms of velocity and direction. Experiments performed by Teye et al. (2008) obtained good relation between theoretical and experimental values for the case of natural ventilation in cattle confinement structures.

5. CONCLUSIONS

From the presented quantification and discussion, the reliability of a given technique for determination of ammonia emission in open or partially open structures can be defined like subjective, however, this given technique may be considered to assist in a certain decision for determining a method, which depends on characteristics of a determined installation operation and the economic resources available, as well as accuracy needed.

The maximal values reached during qualification did not surpass 70% for any of the systems analyzed in terms of their applicability for open animal confinements. This indicates that all methods analyzed should be used depend of each condition of an open structure, especially since the majority of these methods are more efficient in mechanical ventilation systems, making their used in natural ventilation systems more complicated.

6. ACKNOWLEDGEMENTS

The authors would like to thank the National University of Colombia for the great opportunity, Colciencias-Colombia, the Brazilian Government Agency FAPEMIG, the National Counsel of Technological and Scientific Development (CNPq - Brazil) and CAPES for their financial support and the Federal University of Viçosa (UFV-Brazil)

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CHAPTER 4

USE OF THE 3D CFD FOR DETERMINATION OF AMMONIA CONCENTRATION DISTRIBUTION IN NON-INSULATED POULTRY HOUSES WITH NATURAL VENTILATION

ABSTRACT: The understanding of concentration distribution of gases such as ammonia (NH_3) in agricultural installations is of growing importance due to its effect on health and productivity of animals and workers. There are methodologies available for determination of NH_3 in poultry houses by continuous monitoring of gas concentration, but require long experimental periods. Computational Fluid Dynamics is a powerful and efficient tool which allows for prediction of this distribution of gases in real time, which allows for a reduction in the number of experiments, and therefore this technique has been utilized to determine pollutant distribution and wind speeds in closed installations. Based on these facts, the objective of this study was use a CFD to develop and validate a model to determine NH_3 concentration distribution in a non-insulated broiler chicken installation with natural ventilation, typical to subtropical and tropical countries. It was found that the proposed model showed a good statistical correlation with the experimental data, which can be used to predict behavior of NH_3 concentration distribution in real time inside the installation with incident winds from different directions of entrance at the lateral opening of the installation.

Keywords: Computational Fluid Dynamics (CFD), natural ventilation, broiler chickens, ammonia concentration, tropical climates.

RESUMO: O conhecimento acerca da distribuição de concentrações de gases tais como a amônia NH_3 nas instalações pecuárias é cada vez mais importante, devido a seu efeito na saúde e na produtividade dos animais e dos trabalhadores. Existem metodologias usadas em galpões avícolas para determinar essa distribuição de NH_3 através do monitoramento continuo de concentrações de gases mas precisam de longos períodos experimentais. A dinâmica de fluidos computacionais (CFD) é uma ferramenta útil é eficiente que permite predizer essa distribuição de gases em tempo real, que permite diminuir o número de experimentos, embora esta técnica tenha sido mais utilizada para determinar distribuição de poluentes e de velocidades de ar em instalações fechadas. Com base no exposto objetivou-se com este trabalho usar o CFD para desenvolver e validar um modelo para determinar a distribuição de concentrações de NH3 em uma instalação para criação de frangos de corte não isolada aberta com ventilação natural típica de climas subtropicais e tropicais. Encontrou-se que o modelo proposto teve uma boa correlação estatística com os dados experimentais, pelo qual este pode ser usado para predizer num tempo real o comportamento da distribuição de concentrações de NH_3 no interior da instalação com ventos incidentes com diferentes direções de entrada na lateral da instalação.

Palavras-chave: Computer fluids dynamics (CFD), natural ventilation, poultry house, ammonia concentration, tropical climate.

Nomenclature

C_p	Specific heat, W kg^{-1} K^{-1}
$C_{A,\propto}$	Concentration of species A in the gas, g m^{-3}
$C_{A,s}$	Concentration of species A, g m^{-3}
C_{pi}	Predicted value
C_{oi}	Measured value
C_{pm}	Average predicted value
C_{om}	Average measured value
D	Diffusion coefficient, m^2 s^{-1}
h	Convection heat transfer coefficient, W m^{-2}·K^{-1}
h_m	Mass transfer coefficient, m s^{-1}
k	Thermal conductivity, W $m^{-1}K^{-1}$
$\overline{m}$	Velocity component, m s^{-1}
N''_A	Mass flux of NH_3, kg m^{-2} s^{-1}
n	Number of measurements
P	Pressure, N m^{-2}
q_A	Heat flux produced by the birds, W m^{-2}
T	Temperature, K
U	Velocity vector
W	Average weight of the birds, kg

Greek Symbols

ρ	Density, kg m^{-3}
μ_τ	Dynamic fluid viscosity, kg $m^{-1}s^{-1}$

Superscripts

T	Transposition tensor

Constants

a,b	Constants, 2.9 and 0.75

1. INTRODUCTION

Air quality is an important factor in poultry production. Air is the source of oxygen for the metabolism and is also required for dissipation of heat, water vapor, gases generated by decomposition of manure and dust liberated by bedding in the environment. All these factors contribute to polluting and altering the ideal characteristics of the air, and as a consequence, increase the susceptibility to respiratory diseases or harm the productive process (MACARI et al., 2001).

The quality of air in animal production environments has been referenced as a point of interest in studies of environmental control systems, focusing on both the health of animals which live in the confinement and that of workers which spend 4 to 8 hours per day in this environment. Within the context of modern aviculture, studies show the direct influence of the inadequate production environment as one of the factors on which the development of respiratory diseases in birds is based (TINÔCO et al., 2008).

Currently, industrial poultry production in tropical and subtropical countries, as is the case of Brazil, seeks to improve installations and the environment with the intention to develop improvements in poultry performance and reduce production costs in order to maintain competitiveness. Birds are now produced in high density, which modifies the thermal comfort and quantity of manure in the bedding of these environments, generated a potentially greater quantity of gases based on fermentation of this substrate. Among the gases, ammonia (NH_3) is highlighted as being highly toxic but frequently encountered in the air, whose formation is attributed to microbial decomposition of uric acid in manure (TINÔCO et al., 2008).

According to Curtis (1983), the effect of NH_3 on animal health occurs first as a mucous irritant of the eyes and the respiratory pathways (primary effect), that is, it affects the regions of direct contact with the gas. Later, when entering the blood stream (secondary effect) it has a toxic effect on the physiological metabolism of the birds – systematic reaction.

Beker et al. (2004) studied the effects of the NH_3 concentrations of 0, 30 and 60 ppm on performance of broiler chickens, including wounds on the trachea, conjunctivitis, ascites and hematocrit (HCT), finding that pulmonary and trachea wounds increased in function of the NH_3 quantity, indicating the high susceptibility of the birds to acquisition of diseases when submitted to high concentrations.

Some studies such as those performed Kim et al. (2008b) and Mitloehner and Calvo (2008) demonstrate that human beings present irritation of the eyes, nose and throat when exposed to NH_3 concentrations between 20 and 25 ppm for 8 h. Therefore, it is recommended that for workers exposed to this environment for 8 hours per day, concentration levels should not exceed 25 ppm.

Effect of the high concentrations and exposure times to NH_3 on the health and performance of animals and workers is notable, which illustrates the importance of understanding distribution of ammonia concentration inside animal production installations.

Therefore, there are various methods to determine distribution of these NH_3 concentrations at any given moment where the most utilized are systems of continuous monitoring such as the Portable Monitoring Units (PMUs) developed by Gates et al. (2005) and used in the studies performed by Blunden et al. (2008), Sommer et al. (2009) and Pecegueiro et al. (2007), as well as the tracer gas method utilized by Dore et al. (2004) and Scholtens et al. (2004). Both methods present excellent precision, however require permanent use to analyze behavior of NH_3 concentration distributions, where prediction of this behavior is only possible via statistical analysis of the data collected during the various experimental periods.

Models of heat transfer, mass transfer and momentum, based on Computational Fluid Dynamics (CFD), allow for a reduction in the number of experiments and costs, and posterior improvements to the installations after validation of experimental data in real time. This type of tool is becoming commonly more important in the agricultural industry.

Therefore, CFD is a highly viable alternative for evaluation of the behavior of climatic variables inside both vegetation and animal structures (NORTON et al., 2007; OSORIO et al., 2009; NORTON et al., 2009; REYNOLDS, 2009; SEO et al., 2009). It can also be used to analyze distribution of gas concentration such as NH_3 in livestock confinements (SUN et al., 2002; SUN et al., 2004) and in other applications to determine pollutant dispersion

(JAYARAMAN et al., 2006; MAIZI et al., 2009; LABOVSKÝ; JELEMENSKY, 2010).

Despite its ample applicability, the majority of studied developed with CFD for analysis of pollutant distributions, such as NH_3, have been done in closed and low insulated installations for cattle and hogs which are typical to countries with temperate climates (principally in Europe and North America). No known studies are applied to open poultry installations with natural ventilation, non-insulated and typical of tropical and subtropical countries.

Therefore, the objective of this study was use the CFD to develop and validate a model to determine the distribution of NH_3 concentrations in a non-insulated broiler chicken house, open and with natural ventilation. It was sought to obtain a low cost, efficient and widely applicable tool which would allow for real time prediction of the concentration of this type of pollutant in structures common to tropical and subtropical countries.

2. MATERIAL AND METHODS

2.1. Operating conditions

The broiler house that was modeled and simulated is located in the city of Viçosa, state of Minas Gerais, Brazil, and makes up part of the integrated system of the Pif-Paf Alimentos S/A Company. The commercial poultry installation used in this investigation housed 14.000 Cobb chickens, with a housing density of 12 birds m^{-2}.

The poultry house measured 100 m in length and 13.5 m in width, with 3 m of ceiling height, 0.50 m of overhang and a 20° roof inclination angle, oriented in the east-west direction. The experimental poultry house does not possess thermal insulation, as is typical in Brazil and much of South America. Bedding was composed of fresh coffee hulls (subtract easily encountered in the Zona da Mata, Minas Gerais, Brazil), being utilized for the first time in the poultry production cycle.

2.2. Experimental data collection

Collection of experimental data was done during three consecutive days of each distinct week in the life of the birds, being 22-28, 29-35 and 36-48 days into the productive cycle. The experiment was performed while the poultry house was maintained open and with natural ventilation.

2.2.1. Acquisition of experimental data

To determine heat flux generated by the birds, equation (1) was used as proposed by Curtis (1983), which related heat flux to weight of the animal.

$$q_A = aW^b \quad (1)$$

The 1 Wire^{TM} system was used to determine temperature inside the installation each second of intervals, using 36 sensors dividing among the installation and located at three different heights off the floor (0.2, 1.2 and 2.2 m) (Figure 1). The sensors were connected to 120 m of telephone cable, creating a matrix with 3x3x4 observation points. The system adopted for acquisition of experimental data with use of the 1-Wire^{TM} protocol was based on the STRADA system, as performed by Rocha (2008) and Rocha et al. (2008).

A DS9490R USB (Universal Serial Bus) adaptor was utilized and connected to a laptop with an Intel Pentium 100 Mhz processor and 64 Mb of RAM for data transfer from the 1-Wire network.

According to Rocha et al. (2008), energy can be provided to the 1-Wire system by one of two methods, the first with a parasitic feed which is derived from the data transmission conductor requiring only two conductors; or the second, with an external feed, in which three conductors are needed as well as a stable 5 V DC energy source. The second option was not utilized and only the parasitic feed was applied to the entire system.

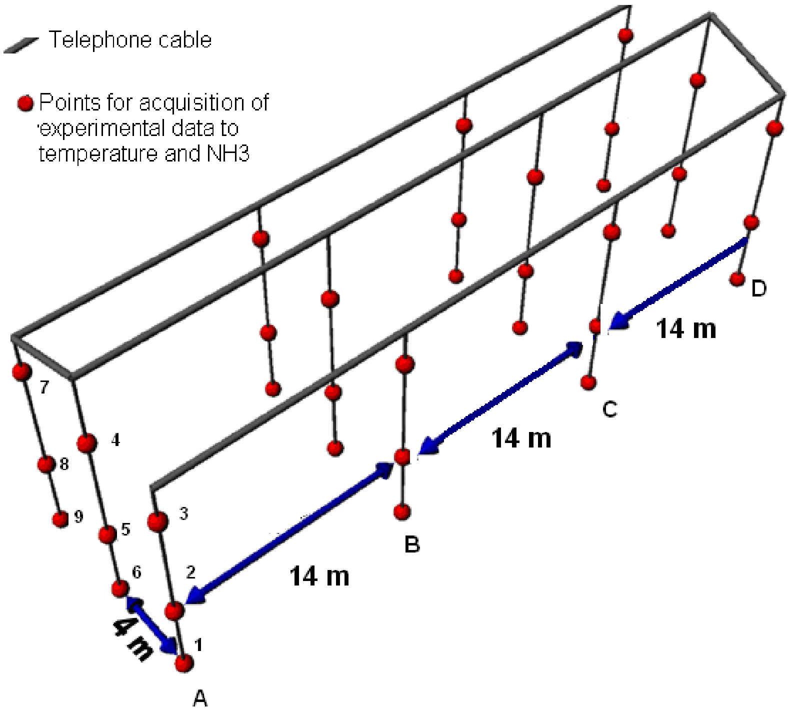

Figure 1 – Distribution of air temperature measuring points inside the poultry house.

The NH_3 concentration data in the environment were obtained by means of a BW electrochemical detector, “Gasalert Extreme Ammonia (NH3) Detector” with a measurement range from 0 – 100 ppm, temperature between -4 and +40°C, relative humidity from 15% to 90% and with an accuracy of ± 2% (to 25ºC between 5% and 95% of RH). Concentration data was measured at each of the 36 points determined in Figure 1, was performed every twenty minutes interval.

For determination of the NH_3 mass flux (N''_A) of the litter the method proposed by Osorio (2011), was used. This method is based on the mass diffusion method for determination of ammonia emissions from chicken litter, by capture of volatilized total ammonia nitrogen (TAN).

Air speed ($m\ s^{-1}$) was measured with a digital wind gage (Testo 425) in each point of the Figure 1, with range between 0-20 $m\ s^{-1}$ precision (°C) ± 0,5, accuracy to 1% (pressure) and 2,5% ($m\ s^{-1}$) and 0,1°C.. Air velocity data collection was performed every twenty minutes interval.

External temperature and relative humidity values were registered with a model HO8, HOBO datalogger, installed in a meteorological station located near the poultry house and 1.5 m off the ground, with resolution of 0.5 °C ± 1% and obtaining data each second with accuracy ±0.7 at 21°C.

Temperatures of the roof and lining were measured with a TD95 model ICEL infrared thermometer, range between -20 a +270ºC, with resolution of 1°C and accuracy of ± 2%.

2.3. Boundary conditions

The measured values obtained experimentally for an open poultry building without thermal insulation and subjected to natural ventilation were used to assign the boundary conditions of the model (Figure 2 and Table 1).

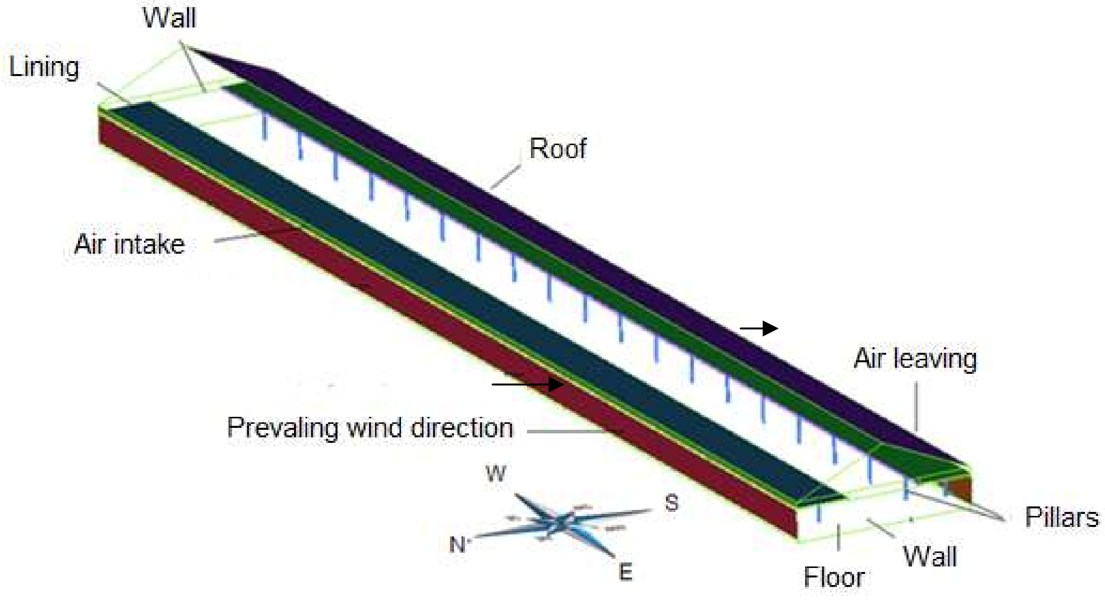

Figure 2 – Diagram of the modeled and simulated installation.

Table 1 – Boundary conditions utilized in the model

Location	Variable	Value
Inlet	Average air speed Air temperature	0.76 m s^{-1} 22.2 °C
Outlet	Manometric pressure Average temperature	0 Pa 23 °C
Lining	Average temperature	24.6 °C
Roof	Average temperature	22.5 °C
Floor	Heat flux generated by the birds (q_A): Mass flux of NH_3 (N''_A):	48.7 W m^{-2} 2.21×10^{-6} kg m^{-2} S^{-1}

2.4. Computational modeling

Due to the geometric complexity of the poultry installation, it was opted to utilize the ANSYS ICEM CFD software for construction of a computational mesh which allows for obtaining results with fewer errors (LEE et al., 2007).

Air flow rates are associated with turbulent flows and, combined with heat transfer rates, generate a complex system of coupled equations difficult to resolve. Therefore, the CFD technique was utilized to solve the average Navier-Stokes and energy equations, determining velocity, temperature and pressure by the finite volumes technique (LAUNDER; SPALDING, 1974). The model for non-isothermal fluid flow is described by the equations of mass, continuity, energy and species, simplified as follows (KIM et al., 2008a).

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho U) = 0 \tag{2}$$

$$\frac{\partial (\rho U)}{\partial t} + \nabla \cdot (\rho U U) = \nabla p + \left[\mu_\tau (\nabla U + \nabla U^T \right] \tag{3}$$

$$\frac{\partial (C_p T)}{\partial t} + \nabla \cdot (-k \nabla T + \rho C_p T U) = 0 \tag{4}$$

$$\frac{\partial C_A}{\partial t} + \vec{m} \cdot \nabla C_A = \nabla \cdot (D \nabla C_A) \qquad (5)$$

Turbulent flow was modeled by means of the k-ε standard model, which evaluates viscosity (μ_τ) from the ratio between turbulent kinetic energy (k) and dissipation of the turbulent kinetic energy (ε). The ANSYS CFX® software belongs to the Department of Agricultural and Environmental Engineering of the Federal University of Viçosa, and was employed to program and simulate the proposed method. The following considerations were assumed: (a) transient regime; (b) incompressible flow; and (c) turbulent flow.

Two computational meshes were generated with different refinement levels using the CFX Mesh computational program, with the objective of verifying effect of refinement on local concentration gradients at the spatial and temporal levels.

2.5. Validation of the model

The results obtained by the CFD method were verified and compared with the corresponding data obtained experimentally in the field. Concordance between the measured values and those described by the CFD model were evaluated by calculating the normalized mean square error (NMSE) (ANDERSON; WOESSNER, 1992). A sample of 40 experimental measurements of all data collected was used. Values of NMSE lower than 0.25 are accepted as good indicators of concordance.

$$NMSE = \frac{\left(\overline{C_p - C_o}\right)^2}{\left(C_{pm} \, . C_{om}\right)} \qquad (7)$$

$$\left(\overline{C_p - C_o}\right)^2 = \frac{\sum_n \left(C_{pi} - C_{oi}\right)^2}{n} \qquad (8)$$

3. RESULTS AND DISCUSSION

A test of the different meshes was done using ANSYS ICEM CFD®. Two types of tetrahedral meshes were used after no significant differences ($p < 0.05$) were encountered for previously evaluated refinement levels, concerning ammonia concentration in the space (Figure 3). Therefore, mesh 1 was selected, composed of 321781 nodes and 1832441 elements (Figures 4 and 5).

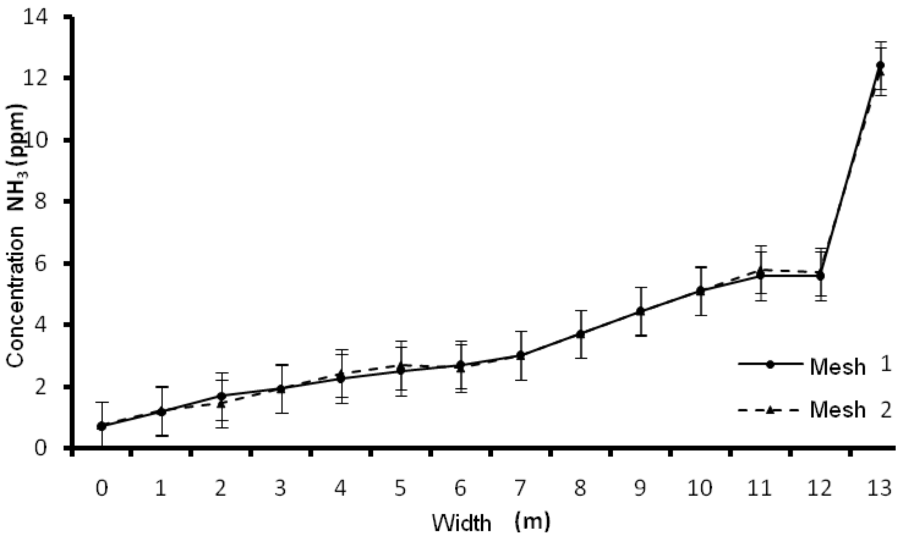

Figure 3 – Test of the meshes: differences between the refined meshes.

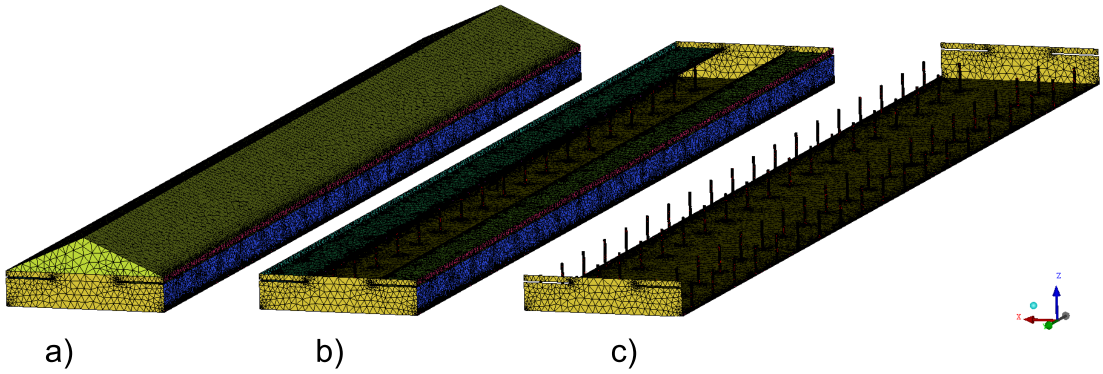

Figure 4 – Computational mesh detail of the installation: (a) external structure, (b) lining below the ceiling, (c) support columns of the structure.

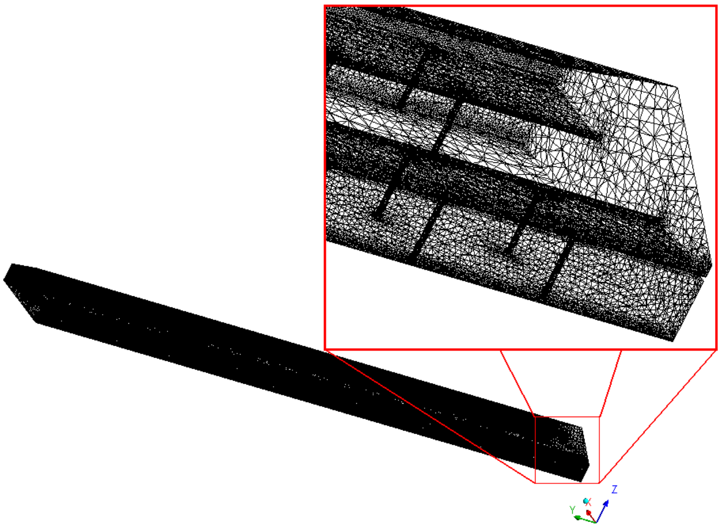

Figure 5 – Refinement detail of the computational tetrahedral mesh.

The experimental values of ammonia concentration obtained in the 36 points presented in Figure 1 do not significantly differ from those encountered when simulating the model with CFD (Table 2 and Figure 6). This is because the NMSE values were less than 0.25, indicating that the CFD model is capable of predicting real operating conditions of the open installation with natural ventilation.

Table 2 – Average of the normalized mean square errors (NMSE) for NH_3 (ppm)

Location	NMSE								
	1	2	3	4	5	6	7	8	9
A	0.0041	0.0082	0.0063	0.0054	0.0049	0.0075	0.0047	0.0066	0.0047
B	0.0065	0.0072	0.0048	0.0075	0.0078	0.0087	0.0082	0.0069	0.0095
C	0.0058	0.0084	0.0044	0.0062	0.0091	0.0065	0.0074	0.0053	0.0086
D	0.0073	0.0055	0.0053	0.0054	0.0067	0.0041	0.0083	0.0064	0.0073

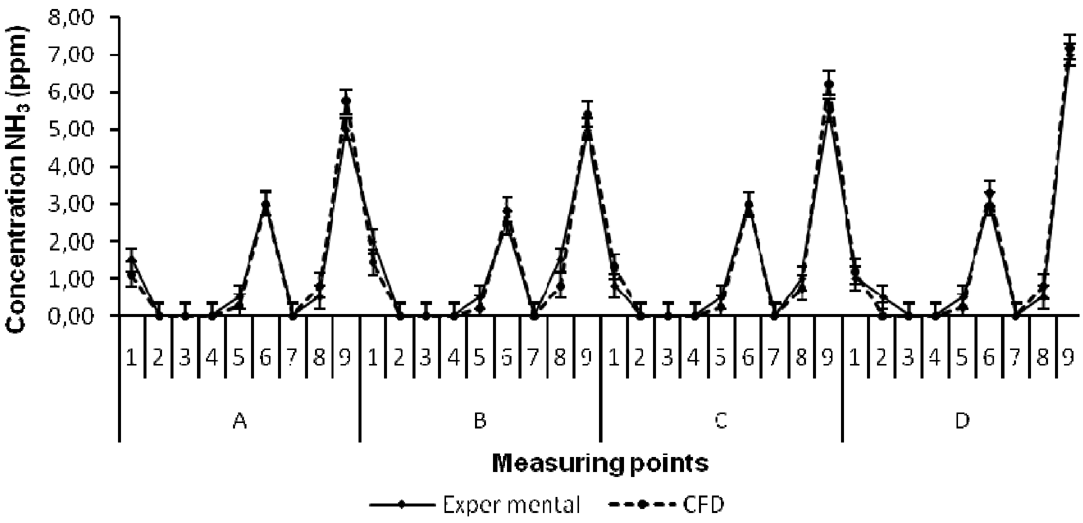

Figure 6 – Differences between NH_3 concentrations measured experimentally and simulated with CFD.

During the period in which this study was developed, it was observed that the predominant winds entering the installation had an entrance angle of 90° and 45°, wind directions referred like the angle between the wind and the building wall plane. It was verified that when the winds entered in a direction perpendicular to the installation (90°), there was a reduction in wind speed due to action of the columns inside the installation, however in the majority of the building there is good uniformity of wind speed distribution. At the height of the birds, 0.20 m, a reduction in wind speed was also observed due to the direct effect of the outer walls and pillars along the perimeter of the installation causing reductions approximately until 20% in wind speeds. This aspect is not desired in conditions of extreme heat and does not favor good thermal comfort conditions (Figure 7).

In the case in which predominant winds enter at 45° it was observed that there is less uniformity of wind velocity inside the installation in comparison with that when predominant winds enter at 90°, an aspect which coincides with results encountered in studies performed by Norton et al. (2009), Seo et al. (2009), Lee et al. (2007) and others.

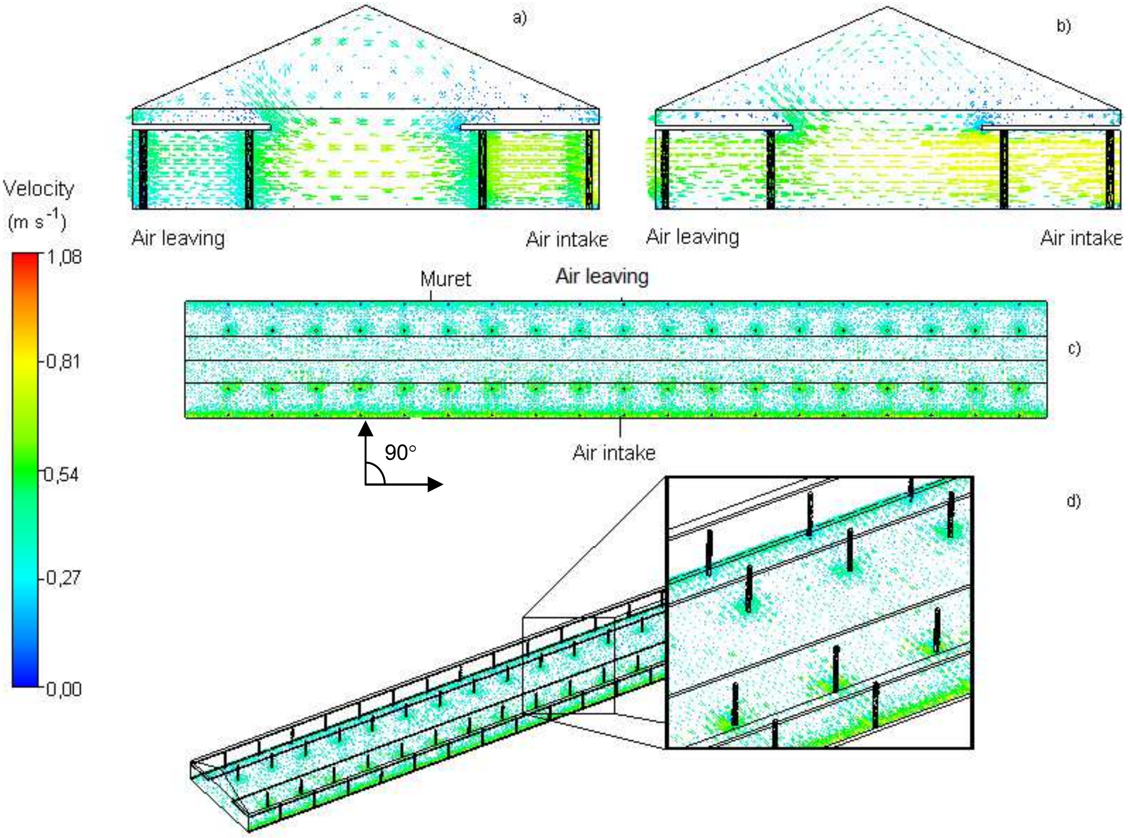

Figure 7 – Velocity vectors inside the building with incident wind entrance of 90°: (a) effect with columns inside the building; (b) effect without columns at the center of the building; (c) plane at the height of the birds (0.20 m); (d) magnification of the velocity vectors

Due to the low distribution uniformity of winds, low wind speeds are presented at the extremities of the installation, which may generate greater gas accumulations in these sectors. Compared to the case in which the predominant winds entered at 90°, it was verified that winds entering at 45° inside the installation at the height of the birds, presented approximately until 10% decrease in velocity, indicating that these were less affected by obstacles such as the wall and columns (Figure 8).

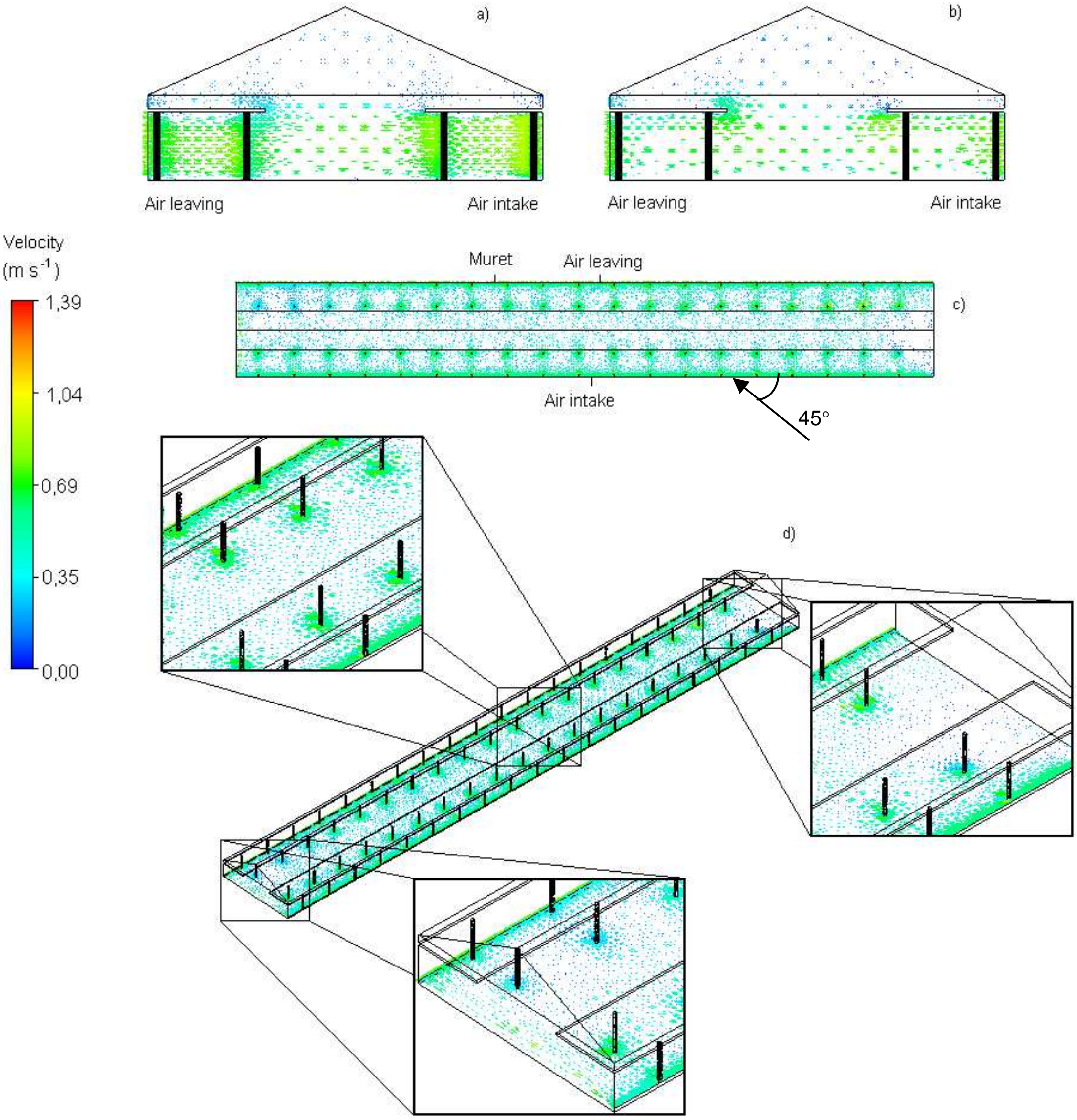

Figure 8 – Velocity vectors inside the poultry house with incident wind entrance at 45°: (a) effect with columns inside the building; (b) effect without columns at the center of the building; (c) plane at the height of the birds (0.20 m); (d) magnification of the velocity vectors.

Figures 9 and 10 present distribution of NH_3 concentration inside the poultry house when predominant winds enter the installation at 90 and 45°. Both cases conformed as expected, in which NH_3 concentrations are greater when there is interference of the pillars, as well an increase in gas concentration near the walls. A reduction of winds in the regions of the walls and pillars, as presented in Figure 7 and 8, may be the principle cause of greater gas concentrations found at the height of the birds, principally where winds exit the installation. This phenomenon was also verified in the field.

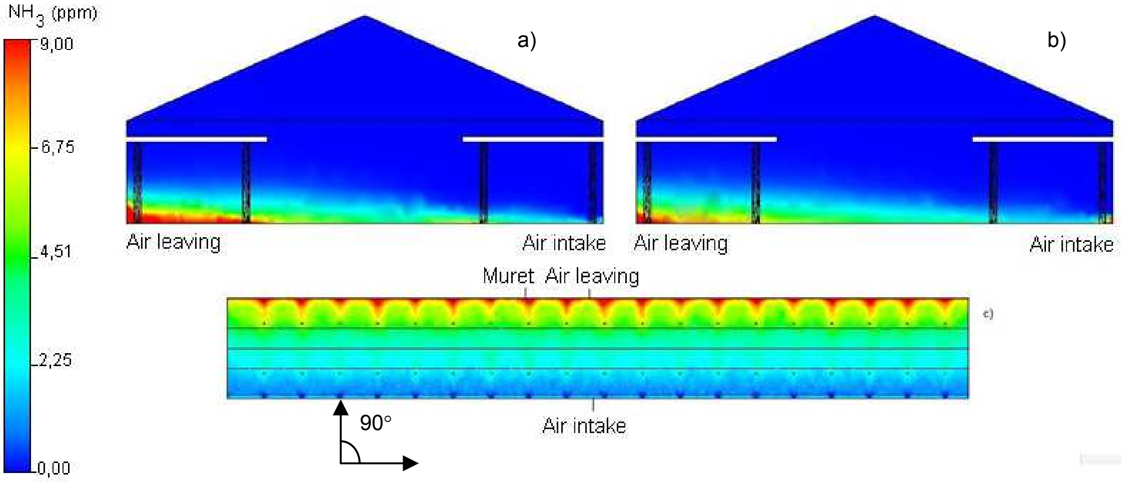

Figure 9 – NH_3 concentration inside the installation with incident winds at 90°: (a) effect with columns; (b) effect without column at the center of the building; (c) plane at the height of the birds.

c)

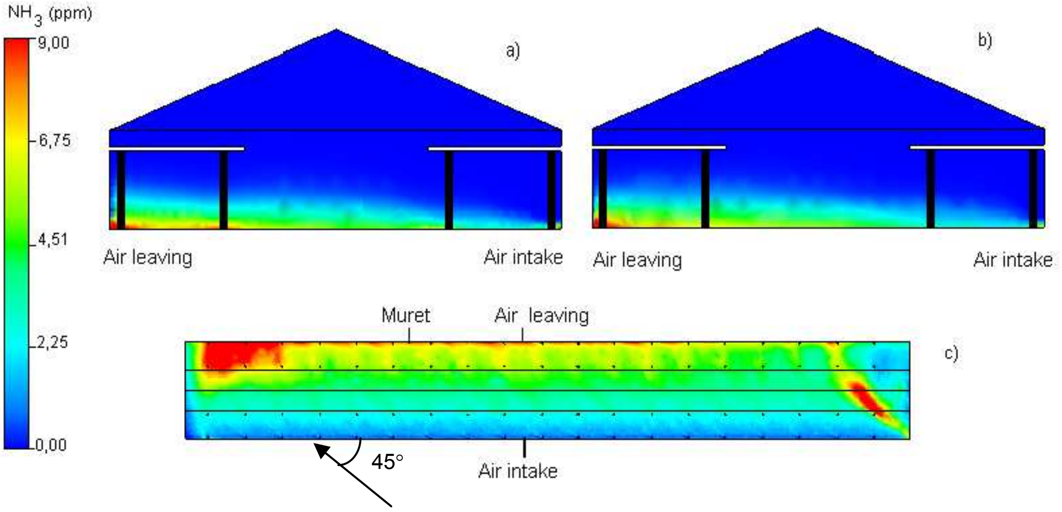

Figure 10 – NH_3 concentration inside the installation with incident winds at 45°: (a) effect with columns; (b) effect without column at the center of the building; (c) plane at the height of the birds.

In the case in which the predominant winds enter at 90°, greater uniformity of gas concentration distribution was also observed in the installation in comparison with winds entering at 45°.

In both cases it was found that NH_3 concentrations at the height of people inside the installation are less than 1 ppm, signifying that during the period in which the installation remains open there is no significant accumulation of gas inside the building since all ammonia generated is emitted by the lateral openings. These results coincide with those encountered in other studies which use other methodologies such as those performed by Osorio (2010), Sommer et al. (2009) and Scholtens et al. (2004), as well as others.

Figure 11 presents NH_3 concentration distribution along the width of the installation, at the height of the birds, where there are different wind speeds entering the building at the angles of 90 and 45°.

In both cases it can be observed that as velocity of the predominant wind increases, ammonia concentrations tend to reduce considerably, principally at the air outlet which is where the greatest ammonia concentrations accumulate.

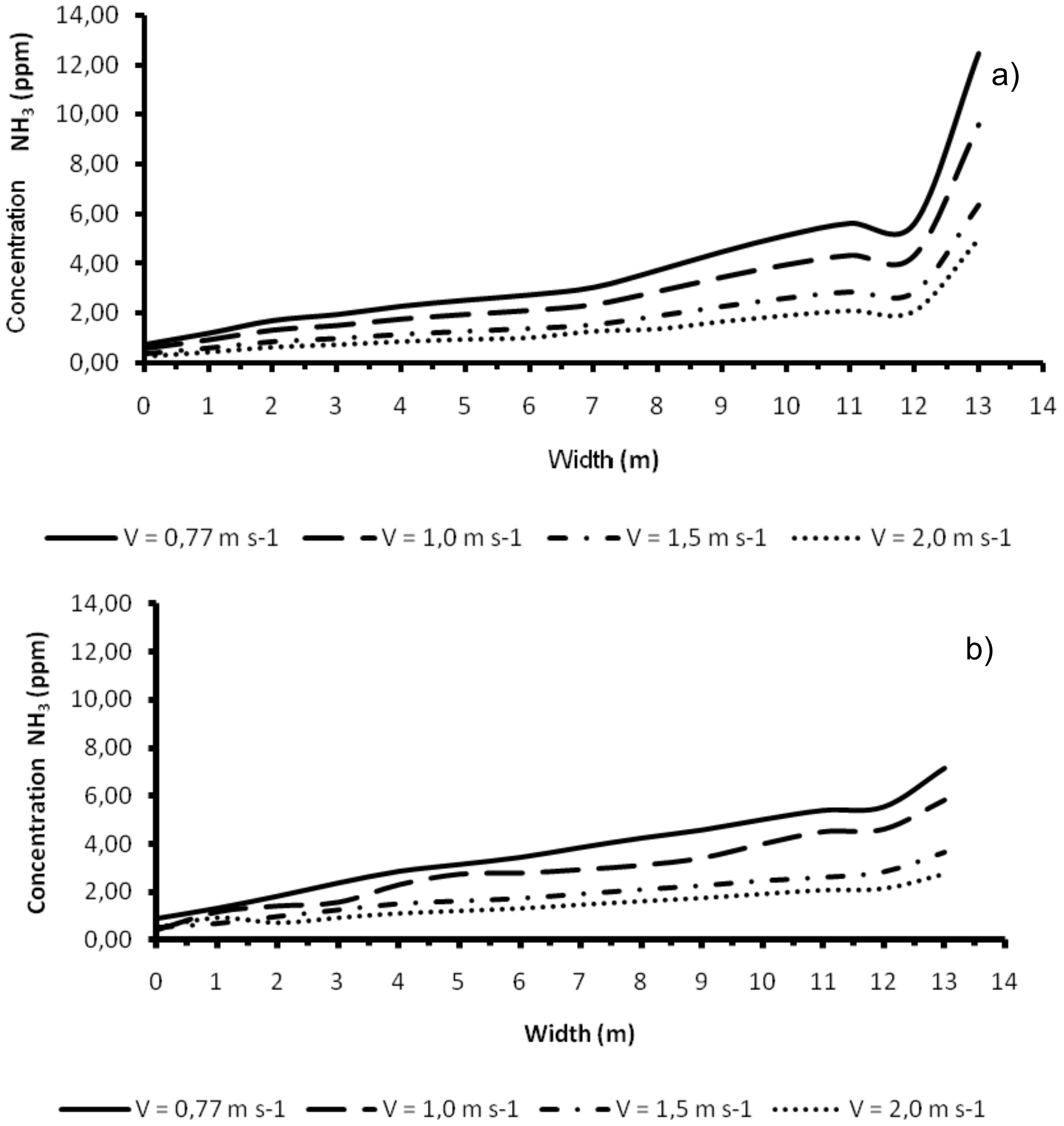

Figure 11 – Ammonia concentrations at the center of the poultry house at the height of the birds (0.20 m) in function of wind speed: (a) with incident wind at 90°; (b) with incident wind at 45°.

It can also be observed that, at the center of the poultry house where there is greater uniformity of NH_3 concentration distribution with winds at 45° compared with those at 90° when presenting the same speeds, NH_3 values along the width of the installation are very similar in both cases. The principle difference is presented in the region where air exits the building, which is due to the fact that wind speeds in this part of the installation are less at 90° in comparison with winds incident at 45° when they have the same entrance velocity, as presented in Figures 6 and 7.

Despite the maximum NH_3 concentrations registered in the experimental time at conditions of natural ventilation, they did not surpass recommendations of the National Institute for Occupational Safety and Health – NIOSH (2001) which are 25 ppm, for an exposure time of 8 hours. At the lateral openings ammonia concentrations are observed on the order 15 ppm with winds at 90° and 8 ppm at 45° at the height of the birds, which directly influences emissions generated by the installation.

In Figure 12 the behavior of NH_3 concentration distribution can be observed at the center of the installation and at the height of the birds (0.20 m) in function of time, with incident winds at 90 and 45°. Once the curtains in the lateral wall are open, in both cases it is observed that variations in ammonia concentrations are minimal after 3 minutes of exposure in the majority of the width of the installation. There are only small variations in ammonia concentration in the region near the air exit (13 m) for which stability is reached after approximately 10 minutes of exposure.

From the result shown in Figure 12, can observe that due to the low ammonia concentrations, may be the ammonia emissions in poultry houses with natural ventilation could be lower in most of the time compared to the emissions generated in broiler house that work in type tunnel with mechanically ventilation and negative pressure, and only could has high emissions in the first minutes after that the laterals curtains of the facility are open, when the ammonia concentrations are higher.

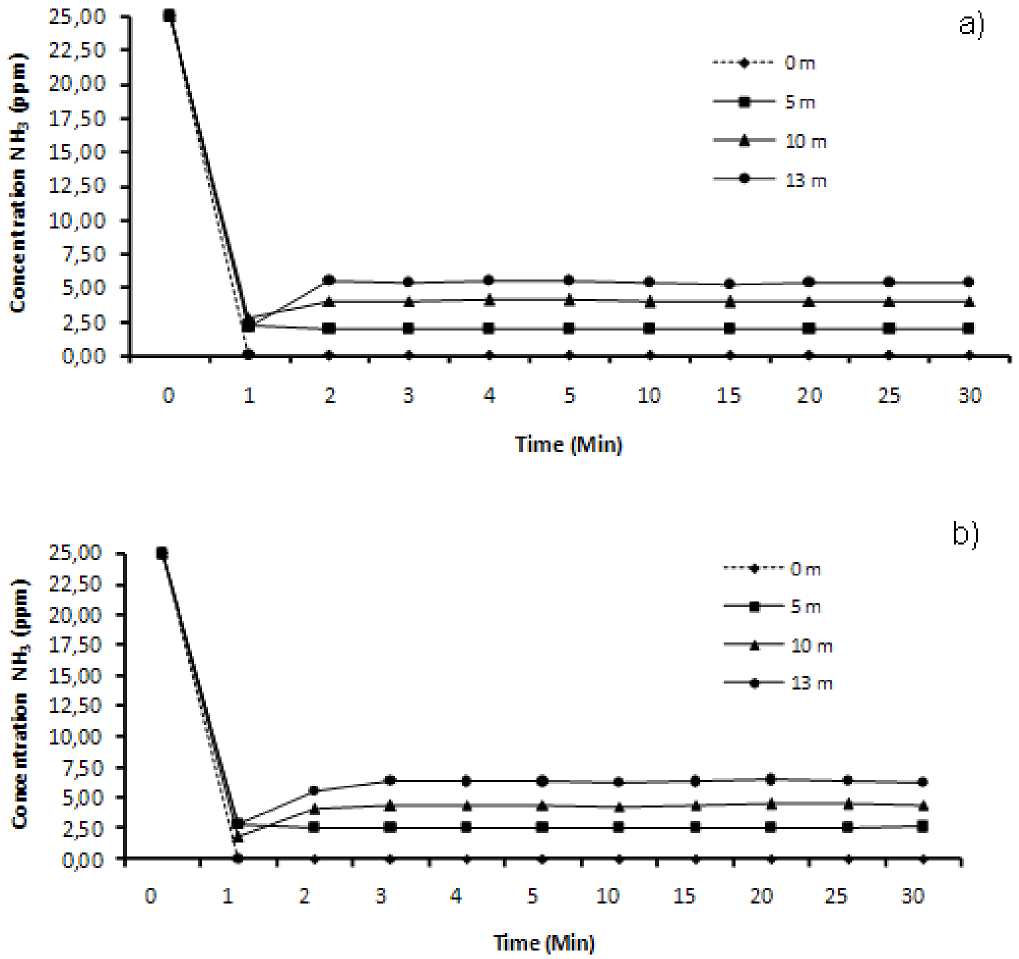

Figure 12 – Ammonia concentration at the center of the installation at the height of the birds (0.2 m) in function of time: (a) with incident wind at 90°; (b) with incident wind at 45°.

4. CONCLUSIONS

The proposed CFD model presented a good statistical correlation with the experimental data, which can be used to predict real time behavior of the NH_3 concentration distribution inside open broiler houses with incident winds in different entrance directions and velocities at the lateral opening.

The CFD model clearly represented the effect of NH_3 concentration near the outer walls and pillars at the exit of the installation. These outer walls, in typical open installations in tropical and subtropical countries, have a height of 0.20 m at the highest. From the results it may be considered to further reduce this height in order to increase wind speed and consequently diminish NH_3 concentrations at the height of the birds. The problem of the pillars in modern poultry buildings in tropical and subtropical climates has already been solved since it is not used in these installations.

The proposed model permits predicting of NH_3 concentrations in function of time when wind speed and direction is constant. However, in field conditions, these parameters vary significantly in function of time. Therefore it is recommended to used maximum values of wind speed, temperature and ammonia mass flux into the model, values considered to be the most critical that can be encountered in real operation of the poultry installations.

To future works, this CFD model could be use to predict the ammonia emissions, due to the knowledge about of the air velocity, temperature and ammonia concentration in different points of the broiler house.

5. ACKNOWLEDGEMENTS

The authors would like to thank the National University of Colombia for the great opportunity, Colciencias-Colombia, the Brazilian Government Agency FAPEMIG, the National Counsel of Technological and Scientific Development (CNPq - Brazil) and CAPES for their financial support and the Federal University of Viçosa (UFV-Brazil)

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CHAPTER 5

APPLICATION OF CFD FOR IMPROVEMENT OF THE NATURAL VENTILATION OF POULTRY HOUSES DURING THE NIGHT FOR TEMPERATURE AND AMMONIA CONCENTRATION CONTROL

ABSTRACT: The objective of this work was to use computational fluids dynamics (CFD) to model and validate a poultry house, aimed at improving conditions of hygiene and welfare in function of natural ventilation which allows for adequate control of temperature and concentrations of ammonia (NH_3). Four different positions of curtain heights or inlet and outlet of air were used, adopting the open building typology without thermal insulation, common to the poultry industry of Brazil and countries with tropical and subtropical climates, where night conditions present temperatures between 10 and 15°C for birds older than 21 days. The validated model presented no statistical differences with the experimental data, making it possible to use this model to predict the behavior of the four proposed cases. The case presenting an air inlet at the height of the lining and an air outlet on the other side of the construction at a height of 0.30 m from the floor presented the best behavior. This is due to the adequate ammonia concentrations at the height of the birds and the temperatures which does not influence performance of animal production.
Keywords: Computational fluids dynamics (CFD), natural ventilation, ammonia concentration, poultry house, natural ventilation, animal welfare.

RESUMO: O objetivo deste trabalho foi usar a Dinâmica dos Fluidos Computacionais (CFD) para modelar e validar um galpão avícola para frango de corte, visando melhorar as condições de higienização e bem estar em função de uma ventilação natural que permita ter um adequado controle da temperatura e dos níveis de concentração de amônia (NH_3). Assim foram delimitadas quatro diferentes posições de alturas de cortinas ou de entradas e saídas de ar, adotadas para a tipologia construtiva aberta e sem isolamento térmico da avicultura industrial do Brasil e de países de climas tropicais e

subtropicais em condições noturnas, com temperaturas que estão entre 10 e 15°C para aves com idades superiores aos 21 dias. As estimativas com o modelo validado não diferenciou estatisticamente dos dados experimentais, pelo que foi possível usar este para predizer o comportamento de galpões tipologicamente similares ao usado neste estudo. O caso que apresenta uma entrada de ar na altura do forro e uma saída de ar no outro lado da lateral a uma altura de 0,30 m do piso foi que melhor comportamento apresentou, já que este permite ter níveis adequados de concentrações de amônia na altura das aves e temperaturas que não influencia no desempenho da produção animal.
Palavras-chave: Dinâmica de fluidos computacionais (CFD), concentrações de amônia, frango de corte, ventilação natural, comportamento animal.

Nomenclatura

C_p	Specific heat, W kg^{-1} K^{-1}
$C_{A,\propto}$	Concentration of species A in the gas, g m^{-3}
$C_{A,s}$	Concentration of species A, g m^{-3}
C_{pi}	Predicted value
C_{oi}	Measured value
C_{pm}	Mean predicted value
C_{om}	Mean measured value
D	Diffusion coefficient, m^2 s^{-1}
h	Convective heat transfer coefficient, W m^{-2}·K^{-1}
h_m	Mass transfer coefficient, m s^{-1}
k	Thermal conductivity, W m^{-1}K^{-1}
$\vec{m}$	Velocity component, m s^{-1}
N''_A	NH_3 mass flux, kg m^{-2} s^{-1}
n	Number of measurements
P	Pressure, N m^{-2}
q_A	Heat flux produced by the birds, W m^{-2}
T	Temperature, K
U	Velocity vector
W	Mean weight of the birds, kg

Greek symbols

ρ	Density, kg m^{-3}
μ_τ	Dynamic viscosity of the fluid, kg m^{-1}s^{-1}

Superscripts

T	Transposition operator

Constants

a,b	Constants, 2.9 and 0.75, respectively

1. INTRODUCTION

The poultry industry of tropical and subtropical countries, such as Brazil, utilizes open poultry houses with no insulation, with only polyethylene curtains to protect against the external environment.

Considering that most of the year is characterized by problems with high air temperatures, generally ventilation and environmental conditioning systems for adult birds prioritize thermal cooling.

However it is worth mentioning that at night-time, especially in regions with harsh winters, the air temperature can drop to levels below the recommended range for thermal comfort of the birds.

In the case of young animals, this problem can be solved or minimized with the use of heating systems in the brooders. However, this practice is not feasible to be employed when the birds are in the adult stage, so to solve this problem producers have adopted the practice of closing the aviary in order to maintain the internal temperature while maintaining some openings located at certain points of the buildings for air renewal.

In the poultry industry of countries with tropical and subtropical climates it is a common practice to carry out sanitary control of poultry houses during night-time conditions in climates with temperatures ranging between 10 and 15°C. This is done using natural ventilation by opening the curtains along the sides of the buildings or mechanical systems with minimal ventilation generated by exhaust fans (TINÔCO et al., 2008; MENEGALE et al., 2009). However, problems have arisen from this practice, such as poor air quality, reduction of temperatures to below the levels of thermal comfort, among others, leading to losses in performance and respiratory diseases.

Each poultry company may practice different combinations of ventilation alternatives since there is still no scientific evidence to define the ideal conditions of operation of the installations at night-time with natural ventilation for broilers with ages of 21 days or more in climates where the temperature varies between 10 and 15°C, which is typical of many regions in Brazil and other tropical and subtropical climates to avoid spending energy on mechanical ventilation.

To be within thermal comfort conditions, some studies, such as those conducted by Esmay and Dixon (1986) and Timmons and Gates (1988), reported that the temperature limits of the thermoneutral zone (TZ) for adult broilers are in the range of 15 to 25°C and can vary depending on their genetic makeup, age, sex, body size, weight, diet and prior exposure to heat (acclimatization).

According to Yousef (1985) and Medeiros et al. (2005), generally the range of dry bulb temperature (tb_s), relative humidity (UR) and velocity of the air (V), which result in increased animal performance, occurred between 21°C and 27°C, 50% and 70%, and 0.5 m s^{-1} and 1.5 m s^{-1}, respectively.

The CFD technique has been applied as a viable method for the behavioral evaluation of climate variables within plant and animal structures (NORTON et al., 2007; BLANES-VIDAL et al., 2008; OSORIO et al., 2009; NORTON et al., 2009; REYNOLDS, 2009; SEO et al., 2009; TINÔCO et al., 2010). This tool is used to analyze the distribution of gas concentrations, such as NH_3 in livestock buildings (SUN et al., 2002; SUN et al., 2004; LABOVSKY; JELEMENSKY, 2010), in addition to analyzing the flow behavior of air in installations occupied by animals and people with different inlet and outlet conditions (GEBREMEDHIN; WU, 2005; STAVRAKAKIS et al., 2008).

Therefore, the objective of this work was to analyze the use of Computational Fluid Dynamics (CFD) to model and validate spatial distribution of temperature and NH_3 concentrations in a typical installation without thermal insulation for the production of broilers in tropical and subtropical climates, with ages greater than 21 days, at night-time conditions for temperatures ranging between 10 and 15°C using four different cases for air inlet and outlet conditions.

2. MATERIAL AND METHODS

2.1. Operational conditions of the experimental installation

In this study a commercial poultry house located near the city of Viçosa, MG, Brazil, was used for the experimental observations, and is part of the integrated system of Pif-Paf Alimentos S/A. The commercial poultry building housed 14,000 Cobb chickens, with a housing density of 12 birds m^{-2}.

The building measures 100 meters long, 13.5 m wide, has a 3 m high ceiling, 0.50 m overhang and roof with an inclination of 20°, oriented in the east-west direction.

The experimental aviary has little thermal insulation, as is typical in Brazil and South America. The bedding was composed of fresh avian coffee hulls, which is replaced for each new production cycle.

Under low temperature conditions, especially at night, the lateral polyethylene curtains of the aviary are closed, thus limiting renewal of air inside the installation.

2.2. Experimental data collection

Experimental data was obtained during three consecutive days in each week of the life of the birds during the night when they were 22-28, 29-35, and 36-48 days old.

2.2.1. Acquisition of experimental data

To determine the heat flux generated by the birds, equation (1) was used as proposed by Curtis (1983), which relates heat flux to weight of the animal.

$$q_A = aW^b \tag{1}$$

A 1 Wire^{TM} system was used to determine the temperature inside the poultry house, including 36 sensors throughout the installation at three different heights from the floor (0.2, 1.2 and 2.2 m) (Figure 1), and temperature data was obtained each second. The sensors were placed using 120 m of two pair internal telephone cable, creating a 3x3x4 array of observation points. The system adapted for acquisition of the experimental data with the 1-wire^{TM} protocol was based on the STRADA system defined by Rocha (2008) and Rocha et al. (2008).

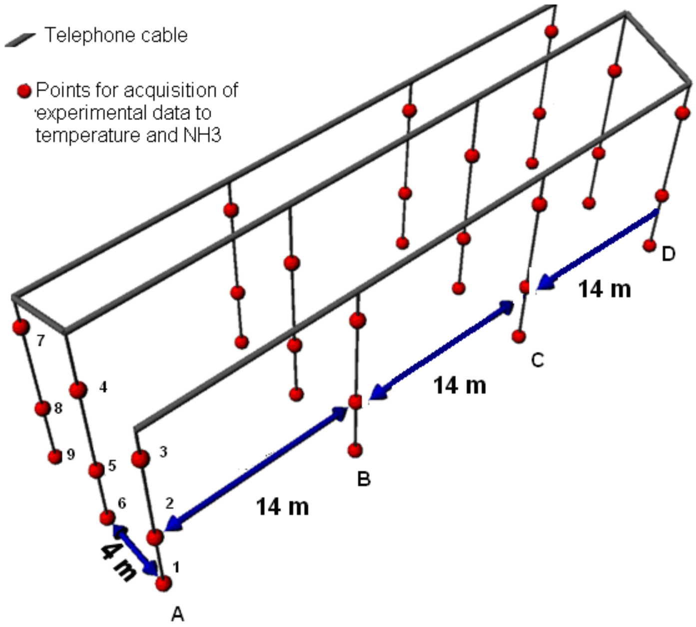

Figure 1 – Dispersion of measuring points inside the installation.

Data of NH_3 concentration in the environment were obtained by means of a BW electrochemical detector “Gasalert Extreme Ammonia (NH3) Detector” with a measuring range between 0 – 100 ppm, between -4 to +40°C, relative humidity between 15% and 90% and accuracy of ± 2% (at 25ºC between 5% and 95% RH), which were measured in each of the 36 points shown in Figure 1 at 20 minute intervals.

The method proposed by Osorio (2010) was used to determine the ammonia flow (N''_A) from the bedding, by capturing the total ammonia nitrogen (TAN) that is volatilized.

Air velocity ($m\ s^{-1}$) was obtained at each of the points in Figure 1, using a digital thermo-anemometer (Testo 425) with the range of 0-20 $m\ s^{-1}$ and accuracy of 1% (pressure), 2.5% ($m\ s^{-1}$) and 0.1°C. Measurements were taken at 20 minute intervals.

Temperatures of the roof and ceiling were measured with an infrared thermometer ICEL model TD95, which had a range from -20 to +270°C, and resolution of 1°C and accuracy of ± 2%.

2.3. Boundary conditions

The values measured in the experimental portion in a closed poultry building with no insulation were used to estimate boundary conditions for the model (Table 1 and Figure 2).

Table 1 – Boundary conditions used in the model

Location	Variable	Value
Inlet	Average air speed Air temperature	0.7 m s^{-1} 18.8 °C
Outlet	Monomeric pressure	0 Pa
Curtains	Average temperature	19.0 °C
Celling	Average temperature	22.5 °C
Floor	Heat flux generated by the birds, (q_A) Mass flux of NH_3 (N''_A)	48.7 W m^{-2} 2.21×10^{-6} Kg $m\text{-}^{2}$ S^{-1}

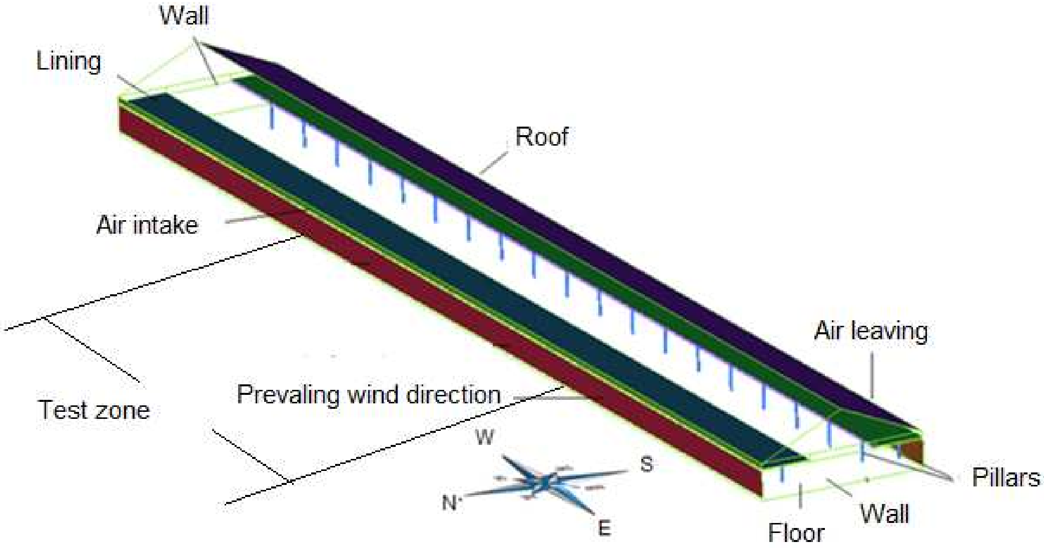

Figure 2 – Schematic of the modeled and studied poultry building.

2.4. Computational modeling

Due to the large geometry of the installation, an experimental and modeled area of 50 meters long by 13.5 m wide was used, with the aim of reducing the computational domain. It was selected to use the software ANSYS ICEM CFD for construction of a computational grid that allows acquisition of results with minimal errors (LEE et al., 2007).

Ventilation rates are associated with turbulent and combined flows with the rates of heat transfer to generate a system of complex coupled equations. Thus, the CFD technique was used for solving the Navier - Stokes and energy equations, discretizing the fields of velocity, temperature and pressure by the finite volume technique (LAUNDER et al., 1974). The model that describes non-isothermal fluid flow is described by the equations of mass, continuity, energy and species, simplified as follows (KIM et al., 2008).

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho U) = 0 \tag{2}$$

$$\frac{\partial (\rho U)}{\partial t} + \nabla \cdot (\rho U U) = \nabla p + \left[\mu_\tau (\nabla U + \nabla U^T \right] \tag{3}$$

$$\frac{\partial (C_p T)}{\partial t} + \nabla \cdot (-k \nabla T + \rho C_p T U) = 0 \tag{4}$$

$$\frac{\partial C_A}{\partial t} + \vec{m} \cdot \nabla C_A = \nabla \cdot (D \nabla C_A) \tag{5}$$

Turbulent flow was modeled using the k-ε standard model, which adds an extra stress (Reynolds stress) in viscosity (μ_τ). This model relates the turbulent kinetic energy (k) and dissipation of turbulent kinetic energy (ε) (LEE et al., 2007).

The software ANSYS CFX®, purchased by the Department of Agricultural and Environmental Engineering of the Universidade Federal de Viçosa, was used to program and simulate the model. The following considerations were made: (a) transient regime, (b) incompressible flow, and (c) turbulent flow. As convergence criterion, the maximum residue of the solution less than 10^{-4} was adapted, for mass, energy and continuity.

Different computational meshes were generated with different levels of refinement using the CFX Mesh software in order to verify the effect of refinement on the local concentration gradients in space and time. Because the installation used a hanging curtain celling during the experimental period, the model generated with the mesh did not take into account the roof.

2.5. Validation of the model

The results obtained by the CFD model were verified and compared with the corresponding experimental data obtained in the field. The agreement between the measured values and those described by the CFD model was evaluated by calculating the normalized mean squared errors (NMSE) (ANDERSON et al., 1992). A sample of 25 experimental measurements of all those collected was used. NMSE values less than 0.25 are accepted as good indicators of agreement.

$$NMSE = \frac{\left(\overline{C_p - C_o}\right)^2}{\left(C_{pm} \, . C_{om}\right)} \tag{6}$$

$$\left(\overline{C_p - C_o}\right)^2 = \frac{\sum_n \left(C_{pi} - C_{oi}\right)^2}{n} \tag{7}$$

2.6. Cases in the proposed CFD model to improve the internal environment in the facilities during the evening

With the objective of improving the hygiene conditions of the poultry houses home to adult birds (over 21 days old) during the night in terms of NH_3 removal and temperature control, four cases have been proposed with different air inlets and outlets, which are most commonly used in real conditions of the poultry industry in tropical and subtropical countries (Figure 3), which are:

a) One air inlet and one outlet measuring 0.40 m, both cases located at Z=0.30 m.

b) One air inlet at the height of the celling measuring 0.40 m in aperture, located at Z = 2.1 m, and an air outlet on the other lateral side measuring 0.40 m in aperture, located at Z = 0.30 m.

c) One air inlet and one outlet measuring 0.40 m in aperture, both located at the lining height at Z=2.1 m.

d) One air inlet with an opening of 0.40 m in aperture at Z=0.30 m, and an outlet with an opening of 0.40 m at the height of the celling at Z=2.1 m.

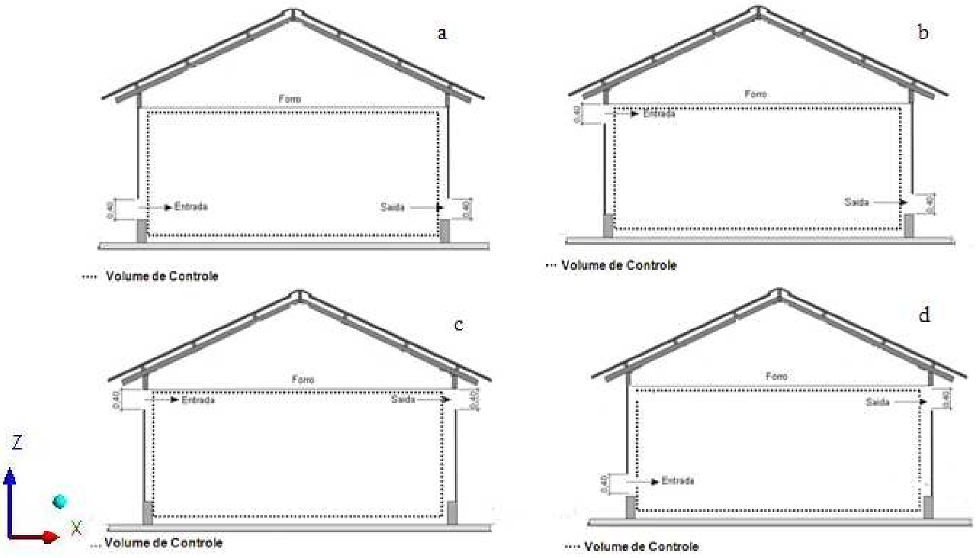

Figure 3 – Schematic of the proposed and simulated cases.

In all cases air renewal is performed by natural ventilation, and is based on the principal that air has one predominant inlet along one of the building walls, which is obtained by generating natural barriers with afforestation which creates pressure differences between the barriers and air intake along the sides of the shed.

Table 2 presents the operating conditions of the various cases used.

Table 2 – Operational conditions utilized in the models

		Cases a,b,c and d
Inlet	Average air velocity (m s^{-1})	0.70
	Air temperature (°C)	11.0
Outlet	Monomeric pressure (Pa)	0.0
Curtains	Average temperature (°C)	12.5
Celling	Average temperature (°C)	21.5
Floor	Flux resulting from the heat generated by the birds (Wm^{-2}), (q_A)	48.7
	Mass flux of NH_3 (kg m-^{2} S^{-1}), (N”A)	2.21 x 10^{-6}

3. RESULTS AND DISCUSSION

A test of the different meshes was carried out using ANSYS ICEM CFD®. Various types of hexahedral meshes were used, and after several levels of previously evaluated refinement, no significant differences ($p < 0.05$) in the concentration of NH_3 were encountered. Thus, the selected mesh possesses 458,450 nodes and 710,334 elements.

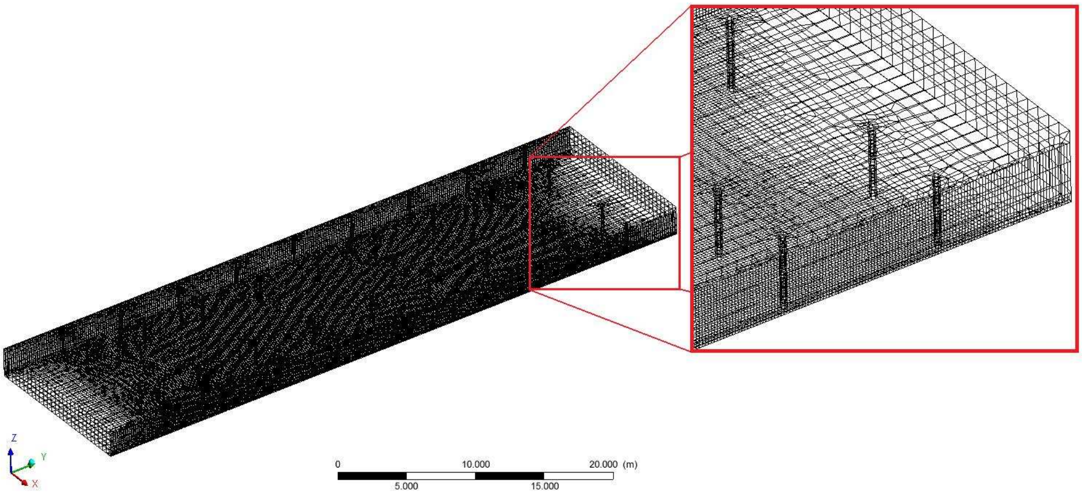

Figure 5 – Detailed view of the hexahedral computational mesh.

The experimental values of ammonia concentration in the 36 points presented in Figure 1 did not significantly differ from those found when the model was simulated with CFD (Table 3). This is because the NMSE values were lower than 0.25, indicating that the CFD model is able to predict actual working conditions closed installation with air inlets for natural ventilation.

Table 3 – Normalized mean squared error (NMSE) for NH_3 (ppm)

Location	NMSE								
	1	2	3	4	5	6	7	8	9
A	0.032	0.072	0.083	0.024	0.039	0.075	0.049	0.076	0.088
B	0.065	0.062	0.064	0.043	0.078	0.042	0.082	0.068	0.071
C	0.082	0.094	0.099	0.035	0.061	0.038	0.093	0.052	0.082
D	0.073	0.077	0.028	0.094	0.084	0.058	0.095	0.068	0.076

Thus, after validating the CFD model, the behavior of temperature distribution and concentration of ammonia inside the poultry houses was analyzed.

Figure 6 shows the behavior of the velocity vectors along the XZ plane of the installation. It can be observed that, in most cases the velocities do not exceed half the velocity of air entering the lateral entrance, which in this case is 0.7 m s^{-1}, the average speed of the regions. In cases *a* and *d*, the air speed at the height of the birds ($0 < Z \leq 0.20$ m) is greater when compared with cases *b* and *c*, which aids in renewal of air and its hygienization.

In each case, these velocities are in the ranges reported by several researchers when observing natural ventilation, although in cases *a* and *d* conditions more suitable for thermal comfort of the animals have been reported (> 0.5 m s^{-1}), according to Madeiros et al. (2005).

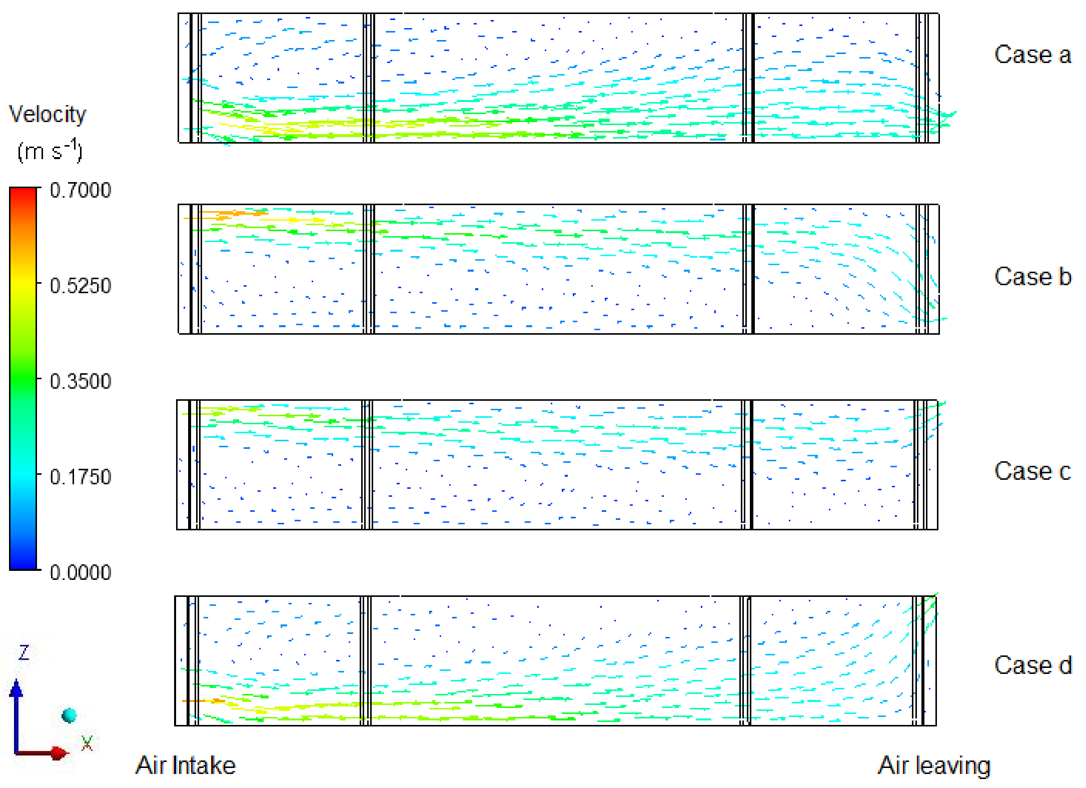

Figure 6 – Velocity vectors for the different cases along the XZ plane of the installation.

The temperature distribution at steady state along the XZ plane of the installation, for the different cases at the height of the birds ($0 < Z \leq 0.20$ m), is shown in Figure 7 and 8. It was found that in cases *a* and *d* temperature ranges between 11 to 17°C at the height of the birds ($0 < Z \leq 0.20$ m), although in case *d* temperatures between 25 and 30°C were encountered in the region near the air outlet ($13 \leq X \leq 13.5$ m). This is due to heat accumulation in this region, since the air outlet is at the ceiling height ($Z = 2.1$ m).

In cases *b* and *c*, between $0 \leq X \leq 1.5$ m, the air temperatures at the height of the birds may reach 32°C due to low air flows that can cause heat buildup, since the air inlet is at the height of the celling ($Z = 2.1$ m). Between $1.5 < X \leq 13.5$ m, temperatures in the range of 20 to 27°C are presented, which coincides with the area of greatest air flow in these cases.

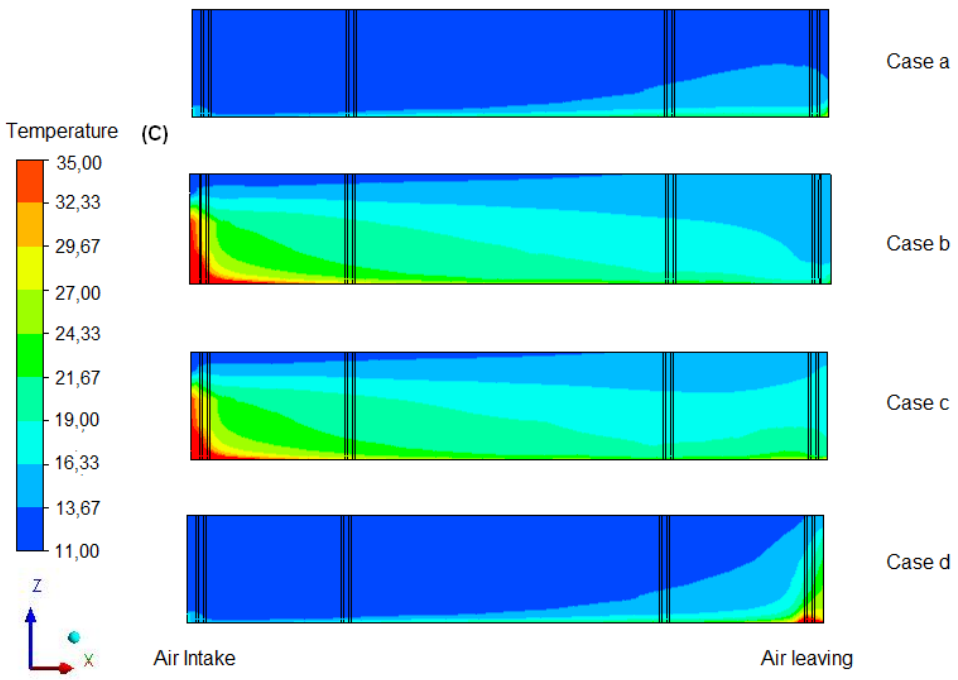

Figure 7 – Temperature distribution along the XZ plane for the different cases.

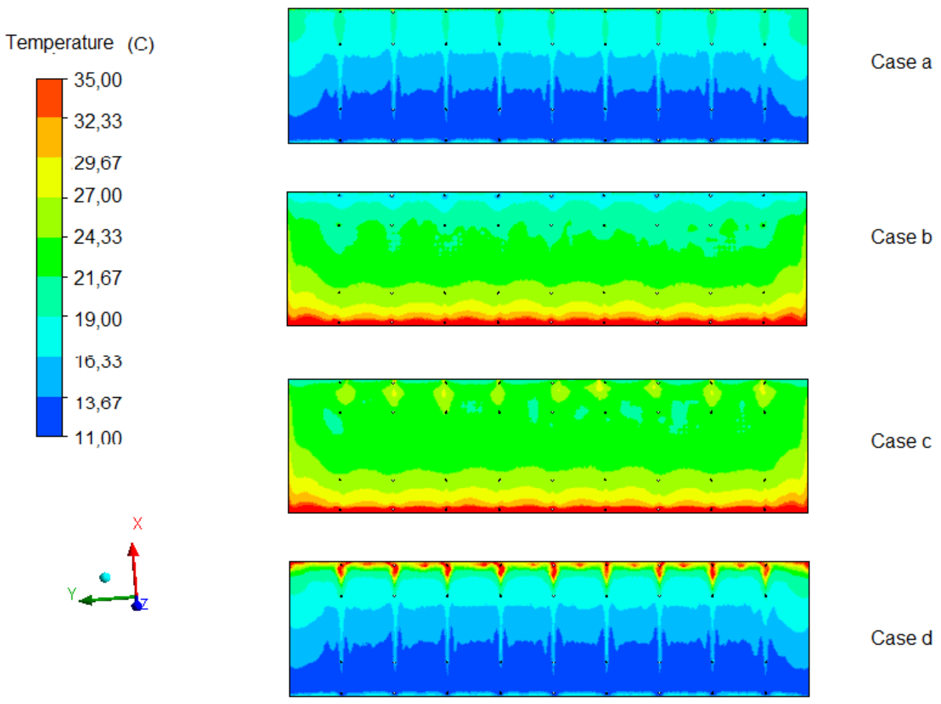

Figure 8 – Temperature distribution along the XY plane at the height of the birds ($0 < Z \leq 0.20$ m) for the different cases.

According to Yousef (1985) and Medeiros et al. (2005), for adult birds (> 21 days old), the best thermal comfort conditions are encountered in the temperature range from 21 to 27°C, although at this age the birds can withstand temperatures of as low as 15°C according to Timmons and Gates (1988). Therefore, the cases which allowed that the majority of the instillation is within this comfort range are cases *b* and *c*.

Figures 9 and 10 show the distribution of NH_3 concentration at steady state along the XZ plane of the installations at the height of the birds ($0 < Z \leq 0.20$ m) for the different cases, respectively. In cases *a* and *d* the NH_3 concentrations presented are between 2 and 16 ppm, although in the case *d,* in the area near the air outlet ($13 \leq X \leq 13.5$ m), concentration values above 30 ppm are presented.

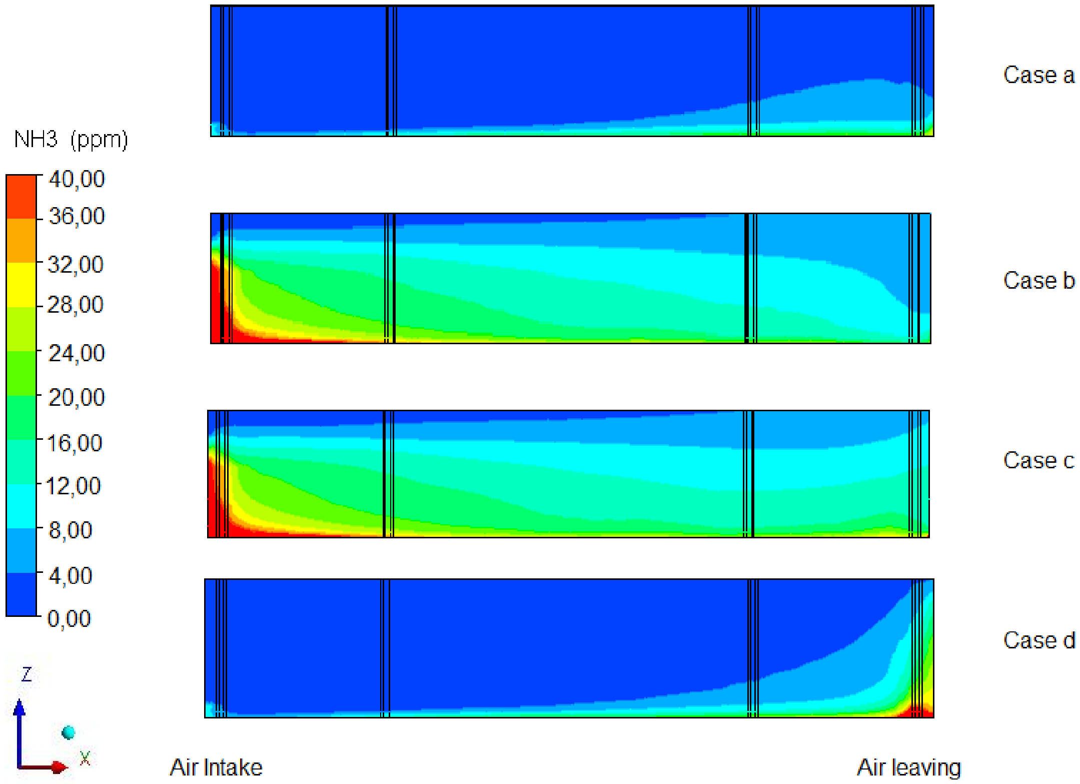

Figure 9 – Distribution of NH_3 concentration along the XZ plane for the different cases.

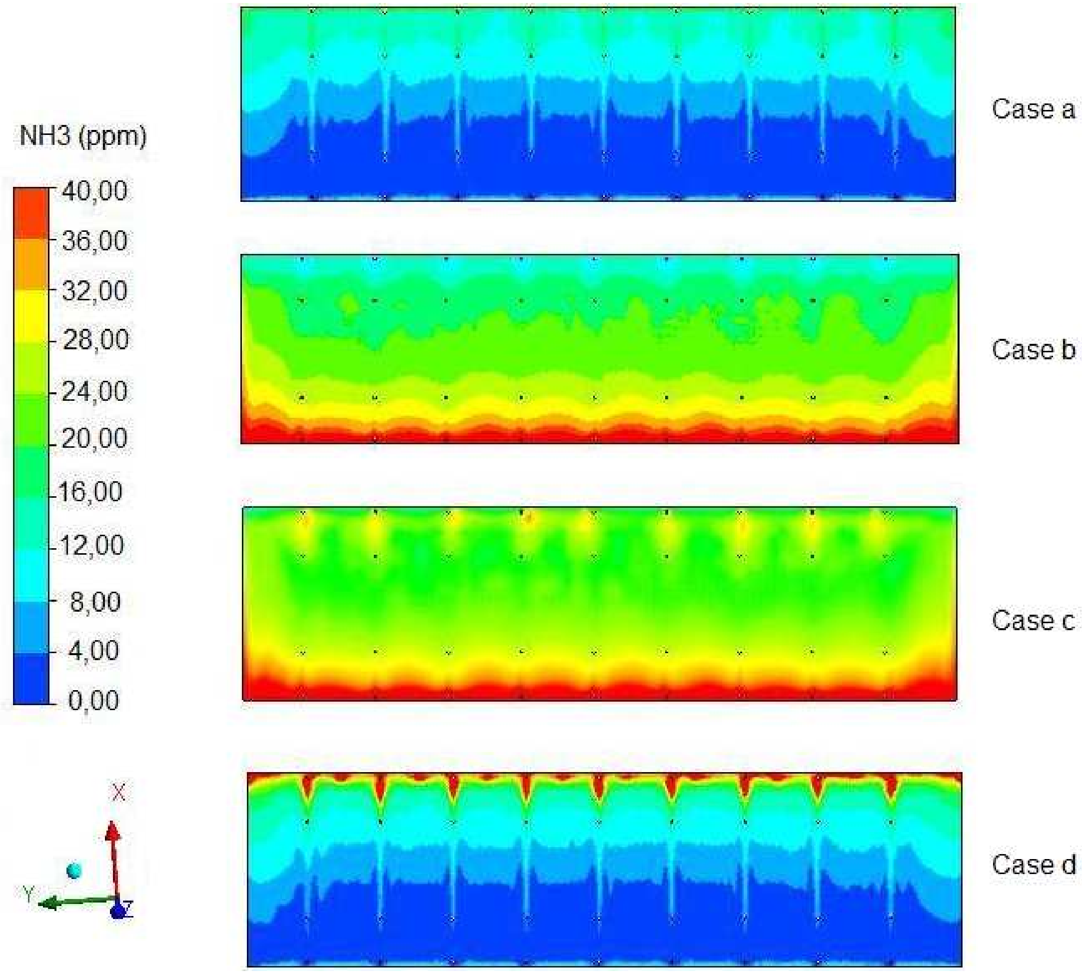

Figure 10 – Distribution of NH_3 concentration along the XY plane at the height of the birds ($0 < Z \leq 0.20$ m) for the different cases.

In case *b*, the ammonia concentrations at the height of the birds are between 18 and 24 ppm and in case *c*, between 20 and 26 ppm. In both cases between $0 \leq X \leq 2.0$, ammonia concentrations between 28 and 32 ppm are presented.

To ensure the health of animals and workers, the National Institute for Occupational Safety and Health – NIOSH (2001) recommended that NH_3 concentrations do not exceed 25 ppm for exposure times up to 8 hours. Thus, according to NIOSH only case *a* presented NH_3 concentrations under 25 ppm, where cases *b*, *c* and *d* presented concentrations greater than this value, which is due to high temperatures and low flow air, as indicated in Figures 7 and 8.

The behavior of temperature distribution as a function of time at the height of the birds ($0 < Z \leq 0.20$ m) for the different cases is shown in Figure 11. In all cases, the initial conditions that cause the inlets and outlets to open are the temperatures of the building reaching those of animal thermal discomfort (28°C).

In case *a*, the temperature inside the instillation begins to decline after about four minutes, and the temperature stabilizes between 11 and 17°C.

In cases *b* and *c*, temperatures as the height of $0 \leq X \leq 1.5$ m continue to increase during the first two minutes until reaching values greater than 38°C, and then decreasing to stabilize at around 32°C. In the remaining area, these temperatures decrease until becoming stable between 20 and 27°C in approximately eighteen minutes.

In case *d*, between $0 \leq X \leq 13.0$ m, the temperature begins to decrease until it reaches 17°C. Near the air outlet ($13 < X \leq 13.5$ m), in the first minute, the temperature continues to rise due to the accumulation of heat in this area, and then begins to decrease until stabilizing in fifteen minutes.

Figure 12 illustrates the behavior of NH_3 concentration as a function of time along the XZ plane at the height of the birds ($0 < Z \leq 0.20$ m) for the different cases. In all cases, the initial conditions causing the inlets and outlets to be opened are the concentration of NH_3 inside the installation reaching 25 ppm.

In case *a* the NH_3 concentrations show to be stable after ten minutes, reaching values between 2 and 16 ppm. In cases *b* and *c* the NH_3 concentrations at $0 \leq X \leq 2.0$ m begin to increase during the first two minutes and then decrease until reaching roughly 30 ppm. Between $2.0 < X \leq 13.5$ m the concentrations decrease and are stable after fifteen minutes at nearly 24 ppm.

In case *d*, near the air vent ($13.0 < X \leq 13.5$ m) high concentrations of NH_3 are observed in the first minutes and then decrease until approaching values near 35 ppm. In the first minute, at between $0 \leq X \leq 13.0$ m, the concentrations begin to decrease until they are stable after fifteen minutes, thus stabilizing at values of approximately 17 ppm.

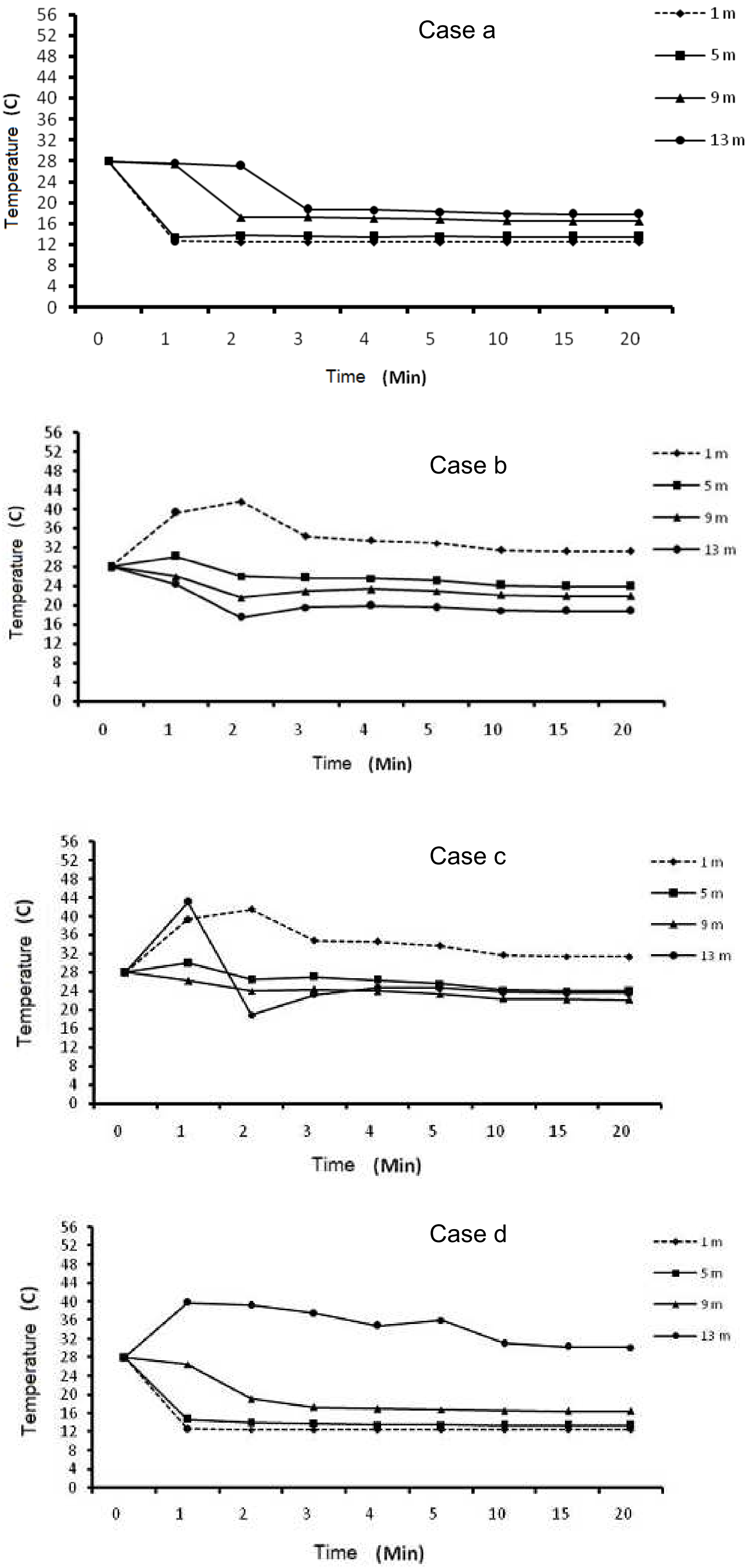

Figure 11 – Behavior of temperature as a function of time at the height of the birds (0 < Z ≤ 0.20 m) for the different cases.

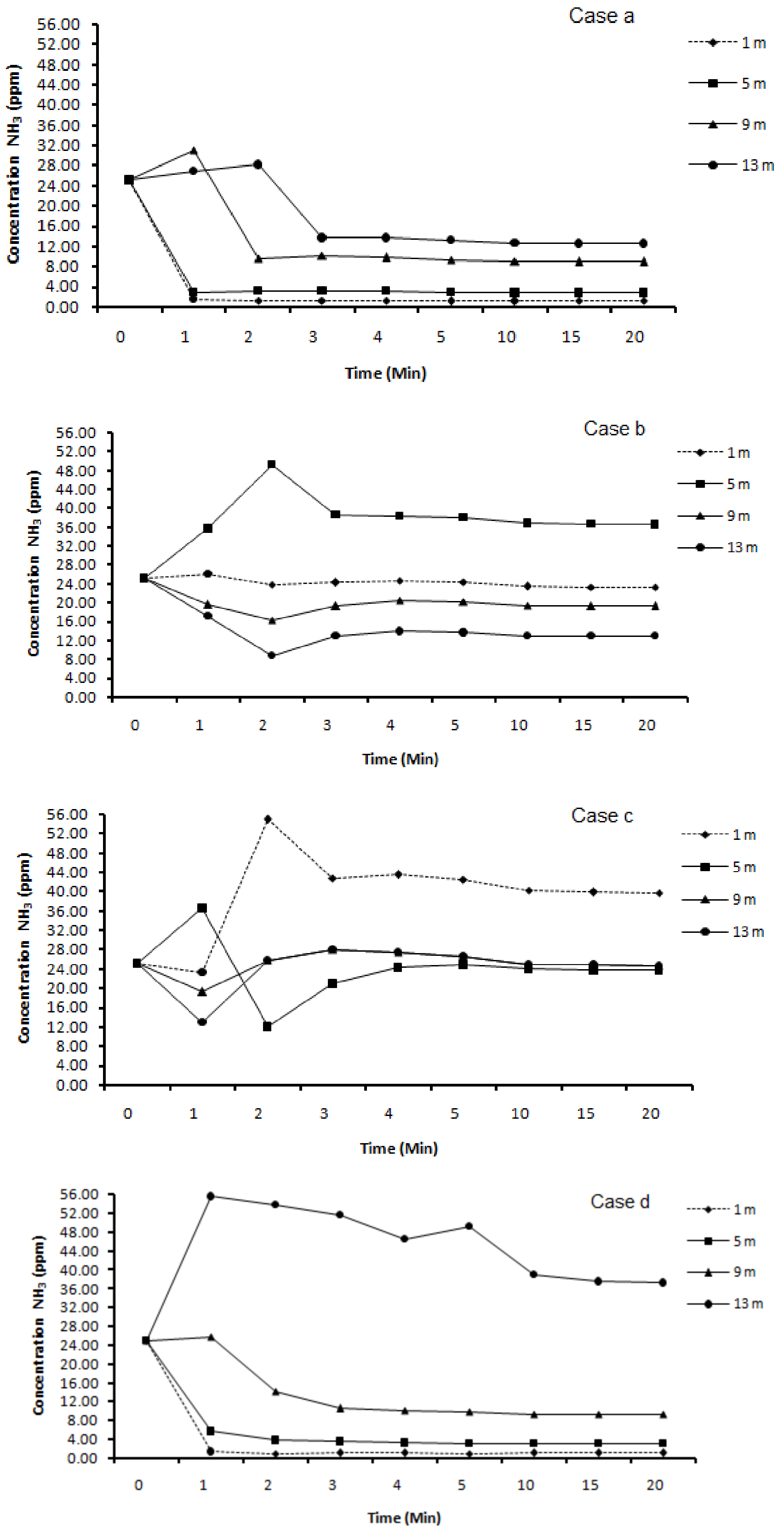

Figure 12 – Behavior of NH_3 concentration at the height of the birds ($0 < Z \leq 0.20$ m) for the different cases.

4. CONCLUSIONS

For this particular type of installation which houses birds older than 21 days, during night-time conditions temperatures range from 10 to 15°C. Of the four cases examined, case *b*, despite showing a small area of the building ($0 \leq X \leq 2.0$ m) with high temperatures and NH_3 concentrations above recommended levels, indicates to be the most appropriate for maintaining good animal hygiene and thermal comfort.

During night-time conditions with adult birds, and with average temperatures of the region between 10 and 15°C, poultry houses may remain under natural ventilation conditions throughout the night-time period in order to maintain a sanitized environment in terms of low NH_3 concentrations and temperatures in the range of thermal comfort.

In cases where outside temperatures are above 15°C, cases *a* and *d* might be most suitable for use in these conditions.

As a suggestion for future studies, in the case in which different operational conditions are presented, the geometry may present some modifications and the internal conditions of the installation may be improved by changing the dimensions of air inlets and outlets to allow for greater or lesser air flow inside the building depending on each specific condition.

5. ACKNOWLEDGMENTS

The authors thank the Universidade Nacional de Colômbia for the opportunity to complete this study, Colciencias Colômbia, the Brazilian government agencies FAPEMIG and CNPq, and the Universidade Federal de Viçosa (UFV - Brasil).

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