LUCIANO BARRETO MENDES

# EVALUATION OF MEANS TO MEASURE EMISSIONS AND AIR FLOWS THROUGH NATURALLY VENTILATED LIVESTOCK BUILDINGS

Thesis presented to the Federal University of Viçosa, as partial fulfillment of the requirements from the Graduate Program in Agricultural Engineering for attaining the degree of Doctor Scientiae.

VIÇOSA
MINAS GERAIS – BRAZIL
2014

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

T
M538e
2014

Mendes, Luciano Barreto, 1983-
Evaluation of means to measure emissions and air flows through naturally ventilated livestock buildings / Luciano Barreto Mendes. – Viçosa, MG, 2014.
xii, 121 f. : il. (algumas color.) ; 29 cm.

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

1. Bovino de leite - Instalações. 2. Frango de corte - Instalações. 3. Ventilação. 4. Gases - Análise. I. Universidade Federal de Viçosa. Departamento de Engenharia Agrícola. Programa de Pós-Graduação Engenharia Agrícola. II. Título.

CDD 22 ed. 636.0831

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Thesis presented to the Federal University of Viçosa, as partial fulfillment of the requirements from the Graduate Program of the Department of Agricultural Engineering for attaining the degree of Doctor Scientiae.

APPROVED: March 12, 2014

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"I do not know what I may appear to the world, but to myself I seem to have been only like a boy playing on the sea-shore, and diverting myself in now and then finding a smoother pebble or a prettier shell than ordinary, whilst the great *ocean of truth lay all undiscovered before me."*

Isaac Newton

## DEDICATION

This thesis is dedicated to all researchers that put out the best of their knowledge as an attempt to address the issue of monitoring air and gaseous patterns in naturally ventilated livestock barns. The studies presented here may one day become obsolete, but I hope that the included findings help towards the progress of the scientific knowledge in this specific field in the years to come.

## BIOGRAPHY

**Luciano Barreto Mendes**, son of José Mendes Irmão and Ana Maria Barreto Mendes, was born in Queimadas, Paraíba state – Brazil, on December 26th of 1983.

In March of 2002 he started to pursue a Bachelor degree in Agricultural Engineering at the Department of Agricultural Engineering of the Federal University of Campina Grande (Campina Grande, Paraíba state, Brazil), graduating in April of 2008. From January to June of 2008, he studied and worked as an exchange student in the Department of Agricultural and Biosystems Engineering (ABE) at Iowa State University (ISU, Ames, Iowa, U.S.A.), under the CAPES/FIPSE Umbrella Agreement.

At the start of the Fall 2007, Mr. Mendes joined the ABE Department at ISU, and in August of 2010 he attained the degree of Master Scientiae (M.Sc.) with major in Agricultural Engineering, in the area of Animal Production Engineering.

In September of 2010, he became a doctoral student at the Graduate Program of Agricultural Engineering of Federal University of Viçosa (Viçosa, Minas Gerais state, Brazil), conducting part of his coursework and research study at Wageningen UR Livestock Research (Wageningen, the Netherlands). Mr. Mendes defended his Doctoral Thesis in March of 2014.

## ACKNOWLEDGMENTS

My primal acknowledgment is given to the One Who allows us all to exist and live, The Creator of nature with its mysterious beauty, which we, scientists and researchers, out of naïve curiosity, scarcely try to scrutinize, and barely understand.

I am eternally thankful to my parents, Ana Maria and José, for always giving me unconditional love, and for teaching since my early years of personality formation until today as a fully grown man, what cannot be taught even in the most prestigious university in the world: to be kind, respectful, honest, work hard, give the best from the heart and always pursue improvement. You have shaped the best of who I am today and are the main reason of what I have accomplished thus far in life. Thank you!

Thank you Professor Ilda for adopting me with open arms to the lovely AMBIAGRO family; for always motivating my hunger of exploring the unknown; seeking professional improvement; and for teaching me that the best way of making a path to success in life is by respecting, helping, and working with people around me.

To Dr. Nico Ogink, for the countless earnest talks on the essentials of pure scientific research values. For guiding me through the scientific method, data processing and presentation, statistical analysis, argument construction and discussion of the results during the preparation of the articles here presented. Thank you for truly and honestly criticizing my scientific work when I needed it.

I dedicate special thanks to all the co-authors of the articles presented in this thesis: Elohanna, Hendrik Jan, Ilda, Jairo, Julio, Keller, Marilú, Nadège, Nico and Robinson. For working together during the experiments, for helping with data processing and statistical analysis and for always being there when I needed careful critical review of the manuscripts. This thesis wouldn´t have been possible without you.

Thank you to the thesis committee members: Dr. Tadayiki Yanagi Jr., Dr. Jadir Nogueira da Silva, Dr. Marcos Oliveira de Paula, Prof.(a) Cecília de Fátima Souza and Prof. Paulo Roberto Cecon, for having accepted my invitation to review, evaluate and judge this thesis. Please receive my sincere gratitude for dedicating your knowledge and expertise and taking the time to carefully go through my thesis, and helping me to improve it.

Thank you all the professors and staff at the Department of Agricultural Engineering (DEA) and the Federal University of Viçosa (UFV) for giving me the honor of becoming part of this big warm family, during these three and a half years. Thank you all from the Livestock Research Institute at the Wageningen University and Research Centre, for adopting me during the 12 months of my stay in the Netherlands, where I went to perform some of the studies that are present in this thesis.

To the Brazilian funding agencies: CAPES, CNPq and FAPEMIG, for funding my pursuit of a Doctor degree, by providing scholarships, funding for research projects and supporting the visit of my co-advisor Dr. Nico Ogink to Viçosa for joint work. Please accept my priceless gratitude.

Thank you to all the valuable people I met during this three and a half years journey, making my academic and personal lives much easier. Friends from AMBIAGRO: Adriana, Conceição, Débora, Diogo, Elohanna, Fernanda, Flávio, Humberto, Jadson, Jairo, Jofran, Juan, Keles, Keller, Kelle, Lina, Luis Henrique, Luiz Gustavo, Márcia, Maria de Fátima, Marilú, Maurílio, Maximiliano, Múcio, Olga, Patrícia, Robinson, Ricardo, Roque, Rui (in memorian), Seu Pedro and Wemerton. To my housemates in Viçosa: Anderson, Carlos, Fábio, Kleber, Luciana and Wagner. To my friends from the Netherlands: Annemieke, Maria Cecília, Dennis, Djai, Eef, Eliana, Emma, Gus, Hendrik Jan, Jacqueline, Jan, Johan, Jorge, Jos, Julio, Kimo, Liansun, Marzi, Nadège, Phuong and Rolland. And to all of you whose names my distracted mind didn´t remember: my big thanks, because you´re the best!

My last, but not least and perhaps the fondest, acknowledgement goes to the man who has helped me seeing the world with different eyes, with more love and amazement to say the least. The man who brought me another kind of balance which includes enjoying life in its simplicity, by showing the way back to basics. To my best friend and lover: Gesuino, we already are life partners…

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## RESUMO

MENDES, Luciano Barreto, D.Sc. Universidade Federal de Viçosa, Março 2014. **Evaluation of means to measure emissions and air flows through naturally ventilated livestock buildings.** Orientadora: Ilda de Fátima Ferreira Tinôco. Coorientadores: Nico W. M. Ogink, Sérgio Zolnier e Márcio Arêdes Martins.

Esta tese foi preparada como uma tentativa de abordar uma série de questões importantes sobre os atuais meios disponíveis para medir emissões gasosas e os fluxos de ar em alojamentos animais com ventilação natural (VN). Cinco foram os principais objetivos que levaram à elaboração desta tese: (1) avaliar o desempenho operacional de um dispositivo de baixo custo para monitoramento de concentrações de dióxido de carbono ($CO_2$) e compará-lo com dois outros métodos padrões; (2) avaliar o perfil de distribuição das razões de mistura entre o poluente amônia ($NH_3$) e os gases marcadores hexafluoreto de enxofre ($SF_6$) e $CO_2$ em um galpão para vacas leiteiras com VN; (3) desenvolver um modelo CFD de um galpão de vaca leiteira com VN implementado com o modelo de produção de $CO_2$ do CIGR; (4) desenvolver e testar um protocolo para medição das emissões de $NH_3$ de um galpão brasileiro de frangos de corte com VN, e (5) calcular fatores de emissão de $NH_3$ de dois galpões brasileiros com VN e ventilação mecânica (VM) para frangos de corte. Cinco artigos foram preparados para responder aos cinco objetivos desta tese, os quais incluem uma variedade de fatores e implicações relacionados a um galpão de vaca leiteiras com VN na Holanda e um galpão de frangos de corte com VN no Brasil. O primeiro trabalho versou sobre a comparação de dois métodos de monitoramento de concentrações de $CO_2$ que são comumente usados para estudos de emissões em alojamentos animais com ventilação mecânica (VM) com um sensor de $CO_2$ de baixo custo, e que é novo para fins de pesquisa, podendo ser mais adequado para uso galpões com VN. No segundo artigo, razões de mistura foram calculadas entre o gás $NH_3$ e um dos dois gases marcadores distintos, o $CO_2$ naturalmente liberado pelos animais e esterco, e o $SF_6$ que foi artificialmente injetado no galpão. O objetivo maior deste artigo foi identificar a região dentro do galpão onde as razões de mistura possuem valores estimados aproximadamente constantes, de modo que taxas de emissão representativas para o galpão possam ser estimadas por meio do método do gás marcador. No artigo número três, um modelo em "Computational Fluid Dynamics" (CFD) de um galpão para vacas leiteiras com VN foi desenvolvido e

implementado com as equações de produção $CO_2$ publicadas pelo CIGR, a fim de revelar os padrões de fluxo de ar e $CO_2$ no espaço interno ventilado. O modelo foi validado com dados de concentração de $CO_2$ medidos experimentalmente em vários pontos dentro do galpão. O quarto artigo versou sobre a determinação do algoritmo mais adequado para estimar as taxas de fluxo de ar e gases através de um galpão de frangos de corte com VN, localizado no Brasil. As estratégias de amostragem testadas consistiram de combinações de dois esquemas diferentes de monitoramento das concentrações gasosas e de duas estratégias de predição da produção de $CO_2$ das aves. O quinto e último trabalho foi uma continuação do quarto artigo, e tratou do cálculo dos fatores de emissões de $NH_3$ ($f_{NH_3}$) de galpões com VN e VM para frangos de corte no Brasil. O método utilizado para calcular os fatores de emissão em ambos os galpões foi o do gás marcador, utilizando-se $CO_2$ naturalmente produzido pelas aves. Os $f_{NH_3}$ calculados foram comparáveis com aqueles encontrados na literatura para as condições do Brasil e em outras partes do mundo. No geral, esta tese demonstra que, apesar das complicações relacionadas ao monitoramento dos fluxos de ar poluentes gasosos através de galpões animais com VN, os fatores de emissão obtidos podem ser comparáveis àqueles relativos a galpões animais com VM. Em síntese, o número de pontos no galpão em que as concentrações de gases serão monitoradas é mais relevante do que a utilização de métodos de medição de alta precisão e dispendiosos. Quando o método de gás marcador é utilizado, atenção deverá ser dada a determinação precisa da taxa de injeção do gás marcador ou a taxa de produção de $CO_2$. É importante também que a razão de mistura entre os gases poluente e marcador seja determinada em vários pontos fora da zona ocupada pelos animais, porém acima dela.

## ABSTRACT

MENDES, Luciano Barreto, D.Sc. Universidade Federal de Viçosa, March 2014. **Evaluation of means to measure emissions and air flows through naturally ventilated livestock buildings.** Adviser: Ilda de Fátima Ferreira Tinôco. Co-advisers: Nico W. M. Ogink, Sérgio Zolnier and Márcio Arêdes Martins.

This thesis was prepared as an attempt to cover a number of questions and concerns regarding the current available means to measure emissions and air flows from naturally ventilated (NV) livestock buildings. Five were the main objectives that led to the preparation of this thesis: (1) to assess the operation performance of a low cost carbon dioxide ($CO_2$) measuring device and to compare it to two other standard methods; (2) to evaluate the distribution of mixing ratios of the pollutant ammonia ($NH_3$) and the tracer gases sulfur-hexafluoride ($SF_6$) and $CO_2$ in a NV dairy cow barn; (3) to develop a CFD model of a NV dairy cow barn implemented with the CIGR $CO_2$ production model; (4) to develop and test a protocol for measuring $NH_3$ emissions from a Brazilian NV broiler house; and (5) to calculate $NH_3$ emission factors from a Brazilian NV and a mechanically ventilated (MV) broiler barns. Five papers were prepared to answer the five objectives of this thesis, which include a variety of factors and implications related to a NV dairy cow barn in the Netherlands and a NV broiler barn in Brazil. The first paper dealt with the comparison between two $CO_2$ concentration measuring devices that are commonly used for emission studies in MV barns with one low cost sensor that is new to research purposes and might be more suitable for NV livestock buildings. In the second paper, we compared mixing ratios calculated with $NH_3$ and two different tracers, the $CO_2$ which is naturally produced in livestock houses and the artificially injected $SF_6$ with the aim of identifying the region within the barn ventilated airspace where mixing ratios are approximately constant, from which representative estimates of emission rates through the tracer gas method can be made. In paper number three, a Computational Fluid Dynamics (CFD) model of a NV dairy cow barn was developed and implemented with the CIGR $CO_2$ production equations in order to reveal the flow patterns of air and $CO_2$ within the ventilated airspace. The model was validated with $CO_2$ concentration data actually measured at multiple points within the barn. The fourth paper was about finding a more adequate algorithm for determining flow rates across a NV broiler barn in Brazil. The tested sampling strategies combined two different sampling schemes for gaseous concentrations and two different strategies to

predict $CO_2$ production from the birds. The fifth and last paper was a follow up of paper number four, and dealt with calculation of actual $NH_3$ emission factors ($f_{NH_3}$) of a NV and a MV broiler barns in Brazil. The method used to estimate the emission factors in both barns was based on a tracer gas, using the $CO_2$ naturally produced by the birds as the tracer. The calculated $f_{NH_3}$ were then compared to those found in the literature for Brazilian conditions and those found in other parts of the world. Overall, this thesis proves that despite the complications related to monitoring air and gaseous pollutant flows through NV buildings, emission factors can be obtained which are comparable to those of MV buildings. In general, the number of points in which gaseous concentrations are being monitored within the barn ventilated airspace with properly calibrated devices is more important than using highly accurate and expensive measurement methods. When the tracer gas method is to be used, focus should be given to accurate determination of the tracer injection rate or rate of production of $CO_2$. It is important that the mixing ratio between pollutant and tracer gases be determined in multiple points outside the animal occupied zone, but above it.

# CHAPTER 1. GENERAL INTRODUCTION

## Introduction

In 2011, the world human population reached the unprecedented mark of 7 billion people, and estimates are that in 2024 it will reach the next milestone of 8 billion people (FAO, 2013). At the same time, the world supply for food is facing dramatic drifts as an attempt to meet the world demand. Industrial agriculture is the primary sector that converts nutrients from their inorganic forms into proteins, carbohydrates, lipids that are essential to sustain the healthy development and maintenance of the human body.

The accelerated increase of human population on Earth that started in the 50s, as suggested by Erisman et al. (2008) can be related to the increase in use of fertilizers. Erisman et al. (2008) also correlated increase in human population to increase of meat and other sources of food grown/produced with artificial Haber-Bosh fertilizers. The production of artificial fertilizer was enabled by the Haber-Bosh method, in which ammonia ($NH_3$) was produced from nitrogen gas. The world´s demand for food, feed and energy is combined with the current exceptional ability of grains of annual and semi-annual cycle in producing enough food and energy for humanity and animal ration.

Consequently, with the relatively low cost of the fertilizers and therefore of animal feed, environmental issues related to the excess of nutrients in some of its many forms exists, causing stagnation or acceleration of certain natural processes (Follet & Hatfield, 2009). There are several means of environmental threats associated with the excess or lack of nutrients, such as: (1) greenhouse gas balance, including emissions of nitrous oxide ($N_2O$) plus interactions with other nitrogen (N) forms, particulate matter and atmospheric N deposition, plus tropospheric ozone ($O_3$). $N_2O$ is now also the main cause of stratospheric $O_3$ depletion, increasing the risk of skin cancer from UV-B radiation; (2) deterioration of ecosystems and biodiversity: including the loss of species of high conservation value naturally adapted to few nutrients. Eutrophication from atmospheric N deposition is an insidious pressure that threatens the biodiversity of many ‘protected’ natural ecosystems; (3) impacts on soil quality, such as over-

fertilization and too much atmospheric N deposition acidify natural and agricultural soils, while a shortage of N and other nutrients leads to soil degradation, which can be exacerbated by shortage of micronutrients, leading to loss of fertility and erosion (Sutton et al., 2013).

A considerable amount of the losses from excess of nutrients occur in intense animal production systems and are related to gaseous emissions. As a reaction to that, over the past three decades, a great deal of research effort has been spent all over the world on the search of appropriate methods for measuring emissions and its limiting factors from livestock confinement buildings. An important aspect to consider when monitoring gaseous emissions from a livestock barn is the kind of ventilation system that it presents. One kind of ventilation system that is popularly applied to livestock barns in temperate climate countries, for most livestock categories, is mechanical ventilation (MV); while another kind of ventilation system, more common in tropical climate regions, is the naturally ventilated (NV) livestock barn. There exists nowadays a general consensus on the methodology for measurement methods of emissions from MV barns; however, measuring air ventilation rates and emissions in NV buildings is still a challenge, due to the large uncertainty and variability associated with these measurements (Calvet et al., 2013; Ogink et al., 2013; Takai et al., 2013).

Currently, no reference method exists for measuring air ventilation rates in NV animal houses. But, a number of different candidate approaches have been suggested (Calvet et al., 2013), such as the tracer gas technique using either natural (Feddes et al., 1984; van Ouwerkerk & Pedersen, 1994; Heber et al., 2001; Blanes & Pedersen, 2005; Xin et al., 2009; Samer et al., 2012; Mendes et al., 2013) or artificial tracers (Demmers et al., 2001; Snell et al., 2003; Wu et al., 2012; Kiwan et al., 2013). The use of carbon dioxide ($CO_2$) as a tracer gas ($CO_2$ mass balance approach) for measuring ventilation and emission rates in livestock building was first described by Feddes et al. (1984). While other artificial tracers have been applied in quite a few research studies, such as krypton-85 ($^{85}Kr$) (Samer et al., 2011a; Samer et al., 2011b; Kiwan et al., 2013), trifluoromethyl sulfur pentafluoride ($SF_5CF_3$) (Schrade et al., 2012), and sulfur hexafluoride ($SF_6$) (Kaharabata et al., 2000; Grainger et al., 2007; Schrade et al., 2012; Wu et al., 2012; Lassey, 2013). The basic premises of the tracer gas method are that the tracer should behave as similar as possible to the target gas, the tracer should be distinguishable from background gases, it should be inert and non-toxic to humans and

the housed animals, and harmless to the environment. However, some studies have shown that not all chosen tracers, behave the same when used for simultaneous determination of pollutant emissions from a ventilated airspaces (Samer et al., 2012; Kiwan et al., 2013). Nonetheless, the comparison of distribution behavior of tracer and pollutant concentrations, as well as their mixing ratios in NV livestock barns is still meager in current literature.

When it comes to sampling gaseous concentrations in NV livestock barns, it becomes a challenging task, given the high variability of distribution patterns normally associated to these environments. For instance, Lefcourt (2002) demonstrated that inadequate selection of sampling positions for ammonia ($NH_3$) in NV animal barns may lead to errors in calculated $NH_3$ emission rates from 50% to over 200% of the actual values. Two different approaches arise from the use of the tracer gas method, depending on the purpose of its use. If the focus is monitoring gaseous emissions from NV buildings, attention should be given to obtaining representative mixing ratio between pollutant and tracer gases that are representative for the entire barn ventilated airspace. On the other hand, if the goal is to determine ventilation rates from these barns, obtaining representative barn concentrations of pollutant and tracer gases is more important. In either case, in order to determine representative mixing ratios or gaseous concentrations, it is important that measurements be taken in as many points as possible. Amongst these gases, $CO_2$ is an important but challenging one to sample. Important because it is released by both the animals and the manure, thus mimicking the dispersion pathways of many of the pollutant gases of interest that are present in livestock buildings. On the other hand, $CO_2$ is challenging to monitor because the currently used measurement instruments are either expensive, or show problems when applied to measure at multiple points, resulting in complex, costly and labor intensive monitoring systems (Heber et al., 2006). Hence, there is an urgent need to find a feasible option for measuring device for semi-continuous spatial and temporal concentrations of $CO_2$ in NV livestock barns.

One possible approach to understand emissions from NV livestock barns is by unraveling the motion patterns of the air and pollutants. This can be achieved in at least two different ways: (1) by installing a dense grid of sensors or sampling ports within the ventilated airspace and monitor pollutant concentrations, air speed and temperature in as many points as possible; or (2) by using Computational Fluid Dynamics (CFD), from

which one can describe air movement models as realistic as possible. While the former approach can be carried out, it is not feasible in most practical situations, due to limitations such as installation costs, maintenance and complexity of the required monitoring system (Bjerg et al., 2013). On the other hand, the use of CFD models could provide promising solutions to understand pollutant pathways and ultimately emissions from NV livestock buildings (Arcidiacono & D´Emilio, 2006). The main requirement of the applicability of CFD models is, nonetheless, that they are properly validated with experimental data, and more than that, not only to average values for the entire barn, but to a grid of points spread within the ventilated airspace. Yet, such validated models have not been presented, this far, to the current literature body.

Finally, the world involvement in monitoring emissions from livestock buildings, finding mitigation strategies as an attempt to restrain environmental impacts and ultimately assembling legislation projects to reduce emissions, doesn´t seem to be a priority in current Brazilian context. Even though at global scale, Brazil is one of the biggest producers and exporters of livestock in the world (MAPA, 2013). In recent years, a few efforts on monitoring emissions conducted in Brazil have evidenced/demonstrated an increasing interest of the scientific sector on that issue (Miragliotta et al., 2004; Medeiros et al., 2008; Osorio, 2010; Lima et al., 2011; Souza & Mello, 2011). However, given the magnitude and variability of Brazilian territorial area and livestock production, the number of studies dedicated to determine emissions from this sector is insufficient/very limited. Furthermore, because the majority of the livestock barns in Brazil are naturally or semi-naturally ventilated (Tinôco, 2001; Nazareno et al., 2009; Menegali et al., 2013), specific methodologies for determination of emission factors in these conditions must be developed, to strengthen the existent database on emission factors of gaseous pollutants from the Brazilian livestock industry.

## Thesis objectives

This is the context in which this thesis was brought up. Knowing that there is an urgent need to assess the methods currently available to monitor emissions and air flows from naturally ventilated livestock buildings, especially those that can be applied to the Brazilian reality. The quest for answers to meet this need constitutes the main objective of this doctoral thesis. In order to meet this general goal, the following specific questions were raised:

1. What kinds of technology are currently available in terms of instrumentation for monitoring $CO_2$ concentrations from naturally ventilated buildings? Are there techniques that are more suitable than others? How do they compare with the "golden standard" methods available and trusted by scientists around the world?
2. When it comes to the use of tracer gas ratio method for monitoring emissions from NV livestock barns, is there a region in the ventilated airspace where gaseous sampling is most appropriate? What happens to the mixing properties of the gases with the air in different regions of the barn? Do different tracers behave differently as compared to the pollutants of interest? If so, which one(s) is (are) more appropriate?
3. How do the air and target pollutants move inside a NV livestock barn under typical outside weather conditions? How can CFD models help unraveling the understanding of release and dispersion of these pollutants from the emission sources?
4. Can the current knowledge available in the literature body on monitoring emissions (e.g. of $NH_3$) from NV buildings be actually applied to the Brazilian scenario, given the unique combination of climate, economic and traditional livestock practices? What kinds of emission factors are obtained and how do they compare to those obtained from studies in other parts of the world?

## Thesis organization

This thesis has been prepared in journal manuscript format, and includes five manuscripts that together help answering the questions raised above, and that meet the main objective of this thesis. Three of the presented research studies were conducted in a naturally ventilated dairy cow barn in the Netherlands and two in a naturally ventilated broiler barn in Brazil. At the end, a final summary chapter was prepared to align the conclusions that were obtained throughout the chapters.

Chapter 2 is entitled "NDIR Gas Sensor for Temporal and Spatial Monitoring of Carbon Dioxide Concentrations in Naturally Ventilated Livestock Buildings", which was submitted for publication to the journal Computer and Electronics in Agriculture.

Chapter 3 refers to a manuscript entitled "Spatial Variability of Mixing Ratios of Ammonia and Tracer Gases in a Naturally Ventilated Dairy Cow Barn", and is currently being considered for publication by the journal Biosystems Engineering.

Following, chapter 4 is about a conference paper entitled "Air Motion Patterns of a Naturally Ventilated Dairy Barn by Means of a CFD Model Tested against the Carbon Dioxide Mass Balance Method". This paper was submitted for poster presentation at the 2014 International Conference of Agricultural Engineering (AGENG 2014), that will be held in Zurich, Switzerland, from 6 to 10 July, 2014. This manuscript contains the first results of the model development, which will be improved after the defense date of this thesis, and will ultimately lead to the preparation of a manuscript for submission to a scientific journal.

Lastly, chapters 5 and 6 deal with the practical use of some of the results discussed in the previous chapters applied to the Brazilian context. Chapter 5 is entitled "A Refined Protocol for Calculating Air Flow Rate of Naturally-Ventilated Broiler Barns Based on $CO_2$ Mass Balance", and was submitted for publication to the Colombian journal Dyna – Medellin. Chapter 6 is a paper called "Ammonia Emissions from a Naturally and a Mechanically Ventilated Broiler House in Brazil", and is being considered for publication by the Brazilian Journal of Agricultural and Environmental Engineering (AGRIAMBI).

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# CHAPTER 2. NDIR GAS SENSOR FOR TEMPORAL AND SPATIAL MONITORING OF CARBON DIOXIDE CONCENTRATIONS IN NATURALLY VENTILATED LIVESTOCK BUILDINGS

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A manuscript submitted to the Journal Computers and Electronics in Agriculture

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## Abstract

Monitoring emissions in naturally ventilated (NV) livestock barns is still a challenge, where direct estimation of the ventilation rate is a problem. The tracer gas ratio method, using $CO_2$ as natural tracer, has been suggested as a pragmatic option to measure emissions without the need to directly estimate the ventilation rate. This method requires, among others, accurate measurements of $CO_2$ concentrations both inside and

outside (background) the barn. Due to the expected spatial variability of air and gaseous flow patterns within the barn airspace, simultaneous monitoring of gaseous $CO_2$ concentrations at multiple points within the NV barn might help to reduce the uncertainty associated to emission measurements. Most of the currently used measurement instruments to monitor $CO_2$ concentrations are expensive, or show problems when switching between multiple points. The aim of this research was to assess the performance of a low-cost Non-Dispersive Infra-Red (NDIR) sensor for intensive spatial and temporal field monitoring of $CO_2$ concentrations in a NV dairy cow house. This was performed by comparing NDIR sensors with two commonly applied methods, a Photo-Acoustic Spectroscopy (PAS) Gas Monitor and an Open-Path laser (OP-laser). The specific objectives of this research were: (a) to test the NDIR sensor in the laboratory for linearity, variability between sensors and sensitivity to ambient static pressure; (b) to compare and validate laboratory and field calibration procedures for use of the NDIR sensors in naturally ventilated (NV) livestock barns; (c) to evaluate the impact of Mean Integration Times (MITs) on the performance of NDIR sensors compared to PAS and OP-laser methods. First, calibrations for the NDIR sensors were obtained in the laboratory and in the field. Then, laboratory and field calibrated sensors were again applied in the field for comparison with the PAS and OP-laser methods in a validation trial. The main conclusions were: (a) The tested NDIR sensor is a feasible alternative to monitor single-point or averaged spatial $CO_2$ concentrations in livestock barns by presenting a small variability between sensors of 5%, a sensitivity to static pressure of 0.08% of the reading per each 1hPa, and yields field measurements with an average uncertainty of 9 %; (b) Field or laboratory calibrated NDIR $CO_2$ sensors for multi-point monitoring of $CO_2$ concentrations in NV livestock barns are recommended, and can be as reliable as the PAS and the OP-laser methods; (c) The effect of using different MITs on the performance of NDIR sensors compared to the PAS and OP-laser methods was negligible.

**Keywords**: ventilation rate, $CO_2$ mass balance, dairy barn, Open path laser, photo acoustic spectroscopy, mean integration time.

# Introduction

Over the past three decades, considerable research effort has been spent on the search of appropriate methods for measuring emissions from mechanically and naturally ventilated (NV) livestock buildings. Measuring air ventilation rates and emissions in NV buildings is still a challenge, due to the large uncertainty and variability associated with these measurements (Calvet et al., 2013; Ogink et al., 2013;Takai et al., 2013).

Nowadays, no reference method exists for measuring air ventilation rates in NV animal houses. However, a number of different candidate approaches have been suggested (Calvet et al., 2013), such as the tracer gas technique using either natural (Feddes et al., 1984; van Ouwerkerk & Pedersen, 1994; Heber et al., 2001; Blanes & Pedersen, 2005; Xin et al., 2009; Samer et al., 2012; Mendes et al., 2013) or artificial tracers (Demmers et al., 2001; Snell et al., 2003; Wu et al., 2012; Kiwan et al., 2013). The use of carbon dioxide ($CO_2$) as a tracer gas ($CO_2$ mass balance approach) for measuring ventilation and emission rates in livestock building was first described by Feddes et al. (1984). This method uses naturally produced $CO_2$ (from the animal and manure) as a tracer. The tracer is therefore homogeneously distributed throughout the building and presents good mixing with most of the target gases found in livestock houses (Pedersen et al., 2008). The $CO_2$ mass balance relies on (a) accurate measurements of $CO_2$ concentration in- and outside the animal barn, and (b) on accurate prediction of the metabolic heat production and accurate registration of the parameters used in the heat production model (CIGR, 2002; Pedersen et al., 2008). Measuring gaseous concentration distribution in NV livestock structures represents a real challenge in research (Calvet et al., 2013). For instance, Lefcourt (2002) showed that incorrect selection of sampling positions for ammonia ($NH_3$) in NV animal barns may lead to errors in calculated $NH_3$ emission rates from 50% to over 200% of the actual values. It is widely recognized that the best position to achieve a representative average gas concentration is at the air outlets of the building; however, in NV buildings inlet and outlet positions are critically dependent on meteorological conditions and local topography, and therefore, the proper selection of inlets and outlets is not trivial (Ogink et al., 2013). The situation becomes even more complex in very open livestock housing structures, where due to the expected high spatial and temporal variability, use of a measurement system with high spatial and temporal resolution may be required. Furthermore, currently used measurement instruments to monitor $CO_2$ concentrations

are often expensive, or show problems when switching between multiple points, resulting in complex, costly and labor intensive systems (Heber et al., 2006).

Currently applied systems to monitor $CO_2$ concentrations from agricultural facilities include Photo Acoustic Spectroscopy (PAS) Gas Analyzer (Hinz & Linke, 1998a; Hinz & Linke, 1998b; Heber et al., 2001; Wheeler et al., 2006; Topper et al., 2008; Xin et al., 2009; Chepete et al., 2012; Mendes et al., 2012; Zhao et al., 2012; Hassouna et al., 2013; Nicoloso et al., 2013); and the Open-Path laser (OP-laser) (Griffith et al. (2002), Grutter (2003), Hashmonay et al. (1999), Eklund (1999) and Piccot et al. (1994), (Amon et al., 2001; Childers et al., 2001; Briz et al., 2009; Barrancos et al., 2013). An important disadvantage of applying either PAS or OP-laser is the high purchase cost, in particular when multiple sampling is required. Due to the large spatial variability in livestock buildings, the use of more inexpensive $CO_2$ monitoring systems, allowing for multiple point sampling may result in similar, or even better, levels of accuracy than using more accurate and more expensive methods. It is crucial that the accuracy of the alternative methods is within acceptable values, and that it is properly compared and calibrated against reliable (currently used) techniques.

Non-Dispersive Infra-Red (NDIR) sensors, a low-cost technology based on the principle of light absorption in the infrared region, have been suggested as an alternative mean to measure $CO_2$ concentrations in NV livestock buildings. The selection of appropriate calibration procedures, sampling scheme and time-resolution is also essential. For instance, Wood et al. (2013) stated that the resolution of integration in discrete measurements may result in biased estimates of fluxes over time. Xin et al. (2009) showed, when comparing ventilation rates (VR) in a broiler house measured with the $CO_2$ mass balance method and the standard summation of all individual fans, that a time resolution below 30 min may result in significant differences between both methods when monitoring $CO_2$ concentrations. On the other hand, Estelles et al. (2010) showed deviations up to 1.5% when calculating VR and ammonia ($NH_3$) emissions from mechanically ventilated livestock buildings, when using different mean integration time (MIT) values, varying from 1 hour to daily basis.

The goal of this study was to assess the performance of a low-cost NDIR sensor for intensive spatial and temporal field monitoring of $CO_2$ concentrations in a livestock building, as compared to the PAS and OP-laser methods. Specific objectives of this research were: (a) to test the NDIR sensor in the laboratory for linearity, variability

between sensors and sensitivity to ambient static pressure; (b) to compare and validate laboratory and field calibration procedures for use of the NDIR sensors in NV livestock barns; (c) to evaluate the impact of MIT on the performance of NDIR sensors compared to PAS and OP-laser methods.

## Material and methods

In order to assess their feasibility for use in NV livestock barns, the NDIR sensors were first tested in the laboratory for linearity, variability between sensors and sensitivity to static pressure. Then, lab calibrations were developed for the sensors and their application in the field was evaluated. The sensors were brought to the field for exposure to actual $CO_2$ concentrations in a NV dairy cow barn, and compared with two other measuring devices, the PAS analyzer and the OP-laser. As a result, field calibrations of the sensors were obtained. Bland-Altman charts were plotted to assess the agreement between laboratory and field calibrations. Finally, laboratory and field calibrated sensors were applied in the dairy barn for comparison with the PAS and OP-laser methods in a validation trial. The uncertainty of estimating $CO_2$ concentrations with the developed calibration equations was assessed by calculating the Normalized Root Mean Square Error (NRMSE). A detailed description of the methods, experimental procedures and data analysis conducted to meet the objectives of this study is provided below.

### Description of the carbon dioxide measuring devices

NDIR $CO_2$ gas sensor: Consists of a portable sensor (model SD-GAS-025, Sensor Data[1] B. V., Rijswijk, The Netherlands) housed in a 0.20L × 0.05W × 0.05H m polyethylene enclosure, with vents though which ambient air enters either by local convection or passive diffusion. Its measuring principle is based on gas absorption of radiation at a known wavelength. The absorption intensity is proportional to the concentration of the gas (Jäger et al., 2005; Frodl & Tille, 2006; Park et al., 2010). Sensor measuring range is 0.2 - 5000 $ppm_v$ of $CO_2$ concentration, sensitivity of 20 ppmv ± 1% of the reading and accuracy of 30 ppmv ± 2%. The NDIR sensors were excited with a voltage of 1200 mV, and connected to a datalogger system (CR1000, Campbell Scientific, Inc., Logan, Utah) located in a shelter placed outside the barn

[1] Mention of product or company names is for presentation clarity and does not imply endorsement by the authors or their affiliations, nor exclusion of other suitable products.

(figure 1). $CO_2$ concentrations were measured every 2s, and 5 min averages were stored by the datalogger.

OP-laser: This device (model GasFinderFC, Boreal Laser, Alberta, Canada) measures the average gaseous $CO_2$ concentration in the air between the laser source and the reflector. It has a sensitivity of 2500 ppmm (2.5 $ppm_v$), scan rate of 1 sample per second, and a path measuring range of 1 ~ 1000 m. The sensitivity depends on the path length and the strength of the absorption line. The OP-laser was set up to measure $CO_2$ concentrations in the central axis or the barn (path length of 64m), at approximately the same level as the NDIR sensors (3 m above slats). A remote retro-reflector (prism like mirror) was installed on the wall at the opposite side of the barn for reflection of the laser beam back to the beam source. Data was stored at every 2 s, downloaded at the end of the measurement period and later filtered for reflection quality and correlation coefficient of the current spectrum for $CO_2$ concentration against the stored reference gases ($R^2 \geq 0.80$), then 5 min averages were calculated.

PAS analyser: Its measuring principle (photo-acoustic spectroscopy) is based on the conversion of light energy into an acoustic signal, which is detected by very sensitive microphones (I.A.I., 2005) placed on the wall of the measurement chamber. The device (model 1312, INNOVA AirTech Instruments A/S, Ballerup, Denmark) was set to measure only $CO_2$ concentrations at a sampling interval of 40 s, 10 s for flushing and an time integration interval of 5 min. The PAS was programmed to monitor dew point temperature ($T_{dp}$) in order to account for cross-interference with moisture in the air. Prior to the beginning of the experiments, the PAS analysers were sent to the manufacturer for calibration for $CO_2$, other gases and crossed interference with water vapour, in order to certify that deviation on concentration measurements was under the tolerance level of 5%.

## Laboratory tests and calibration of NDIR sensors

Prior to their installation in the animal house, the NDIR sensors were tested in the laboratory for output linearity and sensitivity to static pressure. For the test of linearity, span gas at 1952 $ppm_v$ concentration of $CO_2$ was diluted with zero gas ($N_2$) at the percentages of 0, 10, 20, 30, 40, 50, 60, 70, 80, 90 and 100 % of the span gas, resulting in concentrations of 1952, 1756, 1558, 1363, 1168, 977, 778, 586, 390, 197 and 0 $ppm_v$ of $CO_2$, respectively. One NDIR sensor was exposed to gas at each concentration, at a flow rate of 200 ml $min^{-1}$. This flow rate value was proportional to

the average static pressure to which the sensors are exposed during field measurements. After stabilization of the sensor output (mV), a few readings were recorded. Gaseous mixture static pressure and temperature at the entrance to the sensor were kept approximately constant.

For the static pressure sensitivity test, $CO_2$ span gas at 1952 $ppm_v$ was passed through a NDIR sensor at the following relative pressures: 1.5, 4.5, 9.0, 15.0, 23.0 and 33.0 hPa. The relative pressure values were achieved in the laboratory by applying a surplus pressure inside a sealed protecting case where the sensor was housed. After full reading stabilization, sensor raw data was recorded for each static pressure level. Air temperature was kept approximately constant during the test and recorded. The sensitivity of the NDIR sensors to static pressure was calculated according to equation 1.

$$S_{sp} = \frac{\Delta raw}{\overline{raw} \times \Delta sp} \times 100 \quad (1)$$

where:

- $S_{sp}$ - sensitivity of the NDIR to change in static pressure (% of change in raw data per unit in pressure);
- $\Delta raw$ - measured range of raw data (mV);
- $\overline{raw}$ - mean raw data value (mV);
- $\Delta sp$ measured range of pressure (hPa);

To account for sensor individual variability and to allow independent direct comparison with the standard methods, a two-point calibration was developed in the laboratory for every NDIR sensor. Sensors were excited with a voltage of 1200 mV and exposed to calibration gases at 0 $ppm_v$ of $CO_2$ ($N_2$) and 1952 $ppm_v$ (spam) at a flow rate of 200 ml $min^{-1}$. During exposure to each gas, sensors that presented drifted readings were adjusted. Sensor raw data was corrected for the reference static pressure of 1013.25 mbar and then correlated to the reference gas concentrations. This procedure was performed twice for every sensor: before the start of the field measurements, and at the end of the trials. The final calibration equation was obtained by using data from both calibration procedures, resulting in a single equation per sensor.

## Description of the livestock barn

This study took place in a dairy cow barn (figure 1). The barn is located in Bunschoten, in the middle of the Netherlands, is east-west oriented, a roof with 37% slope, and has dimensions of 64 Lenght × 38 Width × 4 Height m (L × W × H). The building envelope is composed of insulated roof and side walls, the lateral openings on both sides are 2.75 m high, protected with stainless steel screens with openings of 5 × 5 cm and has manually operated curtains. In the eastern part of the building there is a deep litter area of 10L × 21W m with maximum housing capacity of 25 dry and pregnant cows. In the central part of the building, 3 double-rows of cubicles (paper chips bedding; 42L × 21W m) are located, with feeding alleys on both sides (north and south), and maximum housing capacity for 150 lactating cows. The last section of the barn is at the most western side, has an area of 13L × 21W m with similar cubicles and bedding system as for the lactating cows, where the heifers are kept (maximum capacity of 40 heifers). Barn cubicles area had slatted walking alleys and an automatic scraping robot. Manure is stored in a deep pit space of 65L × 21W × 2D m located under the slats and cubicles. Manure was removed from the barn twice a year, usually during early spring and fall seasons. The lactating cows had free access to 3 milking robot systems. All cows were kept inside all year long and were fed with roughage (grass and corn silage) concentrate. The data collection and validation trials in the barn were conducted during the summer season, in the months of June, July and August of 2012.

## Field experimental setup and data collection procedure

Prior to each measurement campaign, the OP-laser was installed in the barn to sample the average $CO_2$ concentration in an open-path of 64 m along the central axis of the barn (3 m from the slats, 19 m of distance from each side). For the comparison of NDIR sensors with the OP-laser, 5 sensors were placed in the central axis of the barn (figure 1). The central line of NDIR sensors was located at a height of 3 m above the slats, 19 m from both side walls. The distance between sensors being approximately 13 m, where the first and last sensors were 6 m away from front and back walls. Measurements with both NDIR sensors and OP-laser were taken for a minimum of 48 hours per trial, with a total of 6 trials. To reduce the effect of sensor individual variability, 5 NDIR sensors were in every trial randomly selected from a set of 17 new sensors. Data sets from all trials were pooled together prior to the statistical analyses. In

order to assess the effect of averaging out data from the NDIR sensor when compared with the OP-laser, the average raw data from the five evenly distributed sensors were averaged out into four distinct mean integration times (MITs: 5 min, 15 min, 30 min and 60 min).

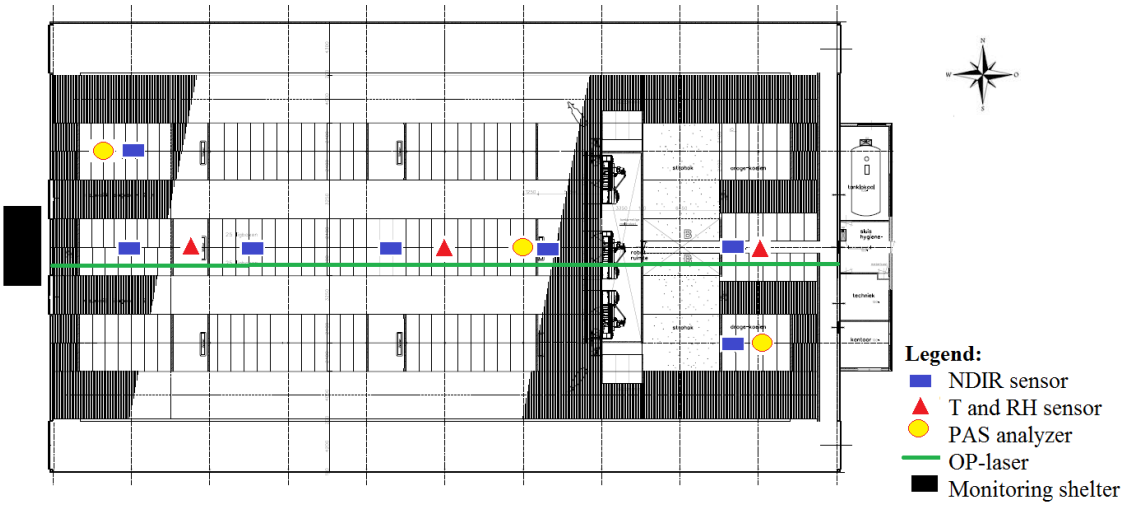


Figure 1. Plan view of the investigated barn with the allocation of the different carbon dioxide ($CO_2$) measuring devices and temperature (T) and relative humidity (RH) sensors (not to scale).

For the comparison of the NDIR sensors with the PAS analyzer, three air sampling ports were installed to collect samples from three fixed different points inside the barn (figure1). The PAS analyzers were placed inside the shelter located at the west part outside the building. The sampling lines consisted of Teflon tubes (0.63 cm internal diameter) with Teflon filters (4.7 cm diameter, 5 µm pore diameter) installed at the end. The air was drawn by the internal pump of the PAS analyzers, with a flow rate of approximately 0.108 $m^3$ $h^{-1}$ during measurements, and 0.018 $m^3$ $h^{-1}$ when flushing the measurement chamber. Each PAS analyzer was programmed to sample $CO_2$ concentrations at every 40s, with 10 s for flushing, and to store average values at every 5 min. Data was downloaded from the analyzers at the end of each measurement. During every trial, three NDIR sensors were installed at the same height and next to each of the PAS analyzers' sampling ports (within a distance of 0.3 m radius) for simultaneous measurement of $CO_2$ concentration. A total of three trials were performed, each lasting a minimum of 48 hr. During each trial, the three used NDIR sensors were randomly selected from a pool of 17 new sensors, in order to reduce the effect of sensor

individual variability. Data sets for all performed trials were pooled together prior to the statistical analyses. The impact of averaging out sensor output in estimating $CO_2$ concentration from PAS analyzer was also performed at four different MIT levels (5 min, 15 min, 30 min and 60 min).

For the determination of local static pressure correction factor ($f_{SP}$), a pressure sensor was installed inside the shelter along with the other instruments, pressure data was stored at every 15 min.

**Regression analysis for field calibrated NDIR sensors**

Regression analysis of the raw data (mV) from the NDIR sensors was performed as a function of the $CO_2$ concentration ($[CO_2]$) measured by either OP-laser or PAS analyzer, with the procedure procreg in SAS®, and fit to a linear model (Equation 2). Additionally, Pearson correlation was carried out on the pooled set of measurements paired in 5, 15, 30 and 60 min intervals.

$$\left[CO_2\right] = A + B \times raw \tag{1}$$

where:

- $[CO_2]$ - carbon dioxide concentration measured with a standard method, either PAS analyzer or OP-laser ($ppm_v$);
- raw - NDIR sensor output data (mV);
- A and B - empirical coefficients obtained from regression ($ppm_v$ and $ppm_v\ mV^{-1}$, respectively).

**Analysis of agreement between laboratory and field calibration methods**

The agreement between the calibration method and each of the standard measurement methods (OP-laser and PAS analyzer) was assessed by regressing the difference between $CO_2$ ($Diff[CO_2]$) concentrations determined with laboratory and field calibration methods and the average $CO_2$ concentration ($Avg[CO_2]$) obtained by both methods by using the analysis of agreement proposed by Altman & Bland (1983):

$$Diff\left[CO_2\right] = \beta_0 + \beta_1 \times Avg\left[CO_2\right] \tag{3}$$

where:

$Diff[CO_2]$ - $([CO_2]_{laboratory\ calibration} - [CO_2]_{field\ calibration})$, difference between $CO_2$ concentrations obtained from the NDIR sensors by using laboratory and field calibrations, $ppm_v$;

$\beta_o$ - Y-intercept, a measure of systematic positive or negative bias, $ppm_v$;

$\beta_1$ - Slope, a measure of non-systematic heterogeneous bias, non-dimensional;

$Avg[CO_2]$ - $([CO_2]_{laboratory\ calibration} + [CO_2]_{field\ calibration})/2$; average between concentration measurements obtained with laboratory and field calibration methods, $ppm_v$.

In equation 3, the intercept ($\beta_o$) and the slope ($\beta_1$) represent homogeneous and heterogeneous systematic bias, respectively. A test of significance for each coefficient was carried on with procreg in SAS® to assess if $\beta_o$ and $\beta_1$ were statistically different from zero.

**Field validation and uncertainty analysis**

After the development of laboratory and field calibrations (obtained from equation 2), the NDIR sensors were once again exposed to $CO_2$ concentrations in the dairy cow barn, next to the standard methods (PAS analyzer and OP-laser) for a period of 48 hrs, with the same setup as done during the comparison trials. Then, $CO_2$ measurements from the NDIR sensors were compared to the standard methods and the NRMSE was determined as a measure of uncertainty. According to Currell & Dowman (2009), for a given linear calibration equation with the shape of equation 2, the NRMSE can be calculated by equation 4.

$$NRMSE = \frac{100}{[CO_2]_{max} - [CO_2]_{min}} \times \sqrt{\frac{\sum_{t=1}^{n} \left([CO_2] - [CO_2]\right)^2}{n}} \quad (4)$$

where:

NRMSE - normalized estimated root mean square error (% over the measured range);

$[CO_2]_{max}, [CO_2]_{min}$ - maximum and minimum measured carbon dioxide concentrations ($ppm_v$), for measurements taken at every 5 min;

$[CO_2]$ - concentration of carbon dioxide measured by the standard (either PAS or OP-laser) method ($ppm_v$);

$\lfloor CO_2 \rfloor$ - concentration of carbon dioxide measured by the field or laboratory calibrated NDIR sensor method ($ppm_v$);

n - number of observations used in the validation.

## Results

### Laboratory tests with the NDIR sensors

The results of the linear regression performed for NDIR sensor raw data against $CO_2$ concentration is presented in figure 2.

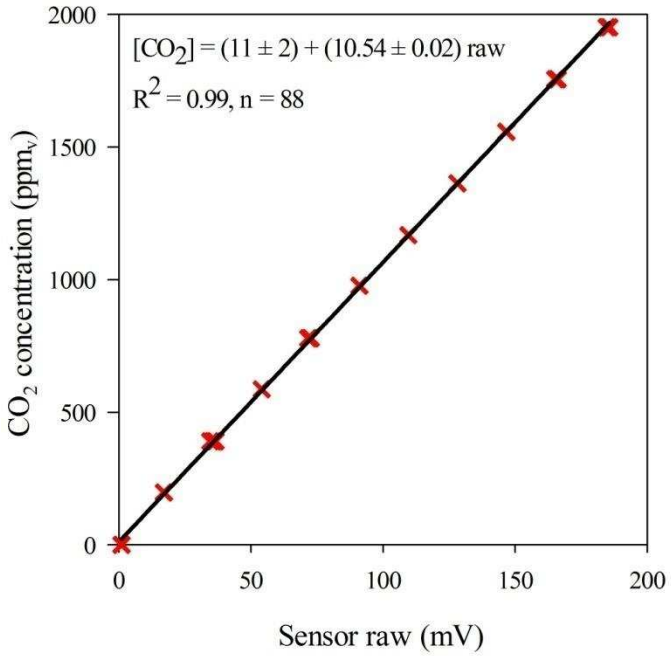


Figure 2. Plot of the linear response of sensor (mV) to calibration gas $CO_2$ concentration ($ppm_v$).

The performed test of linearity indicates that within the range of 0 to 1952 $ppm_v$ of $CO_2$ the sensor had a nearly perfect linear response ($p<0.0001$), with intercept and slope of (-11 ± 2) $ppm_v$ and (10.54 ± 0.02) $ppm_v$ $mV^{-1}$. Such outcome is in agreement with the linearity behavior found by Hodgkinson et al. (2013) within the same range of $CO_2$ concentration levels measured in this study.

The analysis of sensitivity to static pressure yielded a $S_{sp}$ value of 0.08% of the reading per each 1hPa, over the tested range. This result agrees to the specifications of the sensor factory of 0.1% (SenseAir®, 2010). The detected sensitivity to static pressure might be due to effects of pressure on sensor circuitry, causing it to respond slightly differently when static pressure fluctuates around a constant value.

Next to the tests of linearity and sensitivity to static pressure conducted with the NDIR sensors, individual calibration was performed in the laboratory and the results are presented in table 1. In each equation, both the intercept and slope were tested against the hypothesis that the intercept and the slope are significantly different than one and zero respectively. When comparing the coefficients of calibration equations within the 17 sensors presented in table 1, one notices that they present some variability between one another. For instance, when using the sensors to measure a typical $CO_2$ concentration of 910 $ppm_v$, the range of measurements with the different sensors was within 896 to 942 $ppm_v$, resulting in an overall standard error of mean from all 17 sensors of 4 $ppm_v$, corresponding to variability between sensors of 5%.

Table 1. Laboratory two-points individual calibration equations for the NDIR sensors raw data (mV) against $CO_2$ concentration ($[CO_2]$, $ppm_v$), for the linear model of the form $[CO_2] = a + b \cdot raw$

| Sensor ID | a ± SE | b ± SE |
|---|---|---|
| 03062CE1 | -11 ±10 | 10.40* ± 0.30 |
| 03062CD1 | -9 ± 7 | 10.40* ± 0.20 |
| 03062CDF | -9 ± 8 | 10.40* ± 0.20 |
| 0306281F | -9 ± 14 | 10.10* ± 0.10 |
| 0305EFAB | -9 ± 8 | 10.06* ± 0.06 |
| 0306820 | -10 ± 7 | 10.08* ± 0.05 |
| 0306813 | -9.8* ± 0.5 | 10.12* ± 0.03 |
| 03062CE0 | -10* ± 1 | 10.12* ± 0.01 |
| 03062CD5 | -10 ± 6 | 10.13* ± 0.04 |
| 030627C8 | -9 ± 7 | 10.13* ± 0.05 |
| 0305DEF5 | -10.4* ± 0.2 | 10.13* ± 0.01 |
| 03062CD3 | -9.5* ± 0.4 | 10.13* ± 0.03 |
| 030627CA | -9.4* ± 0.2 | 10.13* ± 0.01 |
| 03062CD4 | -10* ± 3 | 10.14* ± 0.02 |
| 03062D34 | -11* ± 7 | 10.61* ± 0.03 |
| 030627CB | -10* ± 3 | 10.13* ± 0.02 |
| 03062C0 | -15* ± 6 | 10.64* ± 0.01 |

*Mean value is significantly different than zero at the level of 95% probability.

The laboratory developed calibration equations presented in this study were obtained with calibration procedures collected over a period of three months, in which

the experimental trials were performed. During this time frame, the drift in calibration coefficients observed in each individual sensor was rather negligible, although over longer times of sensor exposure, significant drifts from calibration might be present. However, effects of long exposure time on sensor calibration equations was not the purpose of this study, and might be a subject for further investigation on field application of NDIR sensors.

**Field calibration of individual NDIR sensors with PAS analyzers and OP-laser**

The results of the field calibration of the NDIR sensors with the PAS analyzers and OP-laser are presented in figure 3 and 4, respectively, for different MIT values. The regression analysis indicated that the data presented good fit to a linear model ($p<0.0001$). The similarity amongst intercept and slopes for different MITs shown in figures 3 and 4 indicates that its effect on the concentration value is considered negligible. Namely, varying MIT from 5 to 60 min yielded regression coefficients that varied from (8.60 ± 0.04) $ppm_v$ $mV^{-1}$ to and (8.78 ± 0.06) $ppm_v$ $mV^{-1}$ for the field determined calibration equations of the NDIR sensors compared to the PAS analyzers.

The regression coefficients varied from (10.01 ± 0.04) $ppm_v$ $mV^{-1}$ to (10.2 ± 0.1) $ppm_v$ $mV^{-1}$ for the field determined calibration equations of the NDIR sensors compared to the OP-laser. The data presented in figures 3 and 4 show that both calibration methods presented strong correlation ($R^2$ = 0.87 - 0.97 and $R^2$ = 0.94 - 0.96 for calibration of NDIR with PAS analyzers and with OP-laser, respectively).

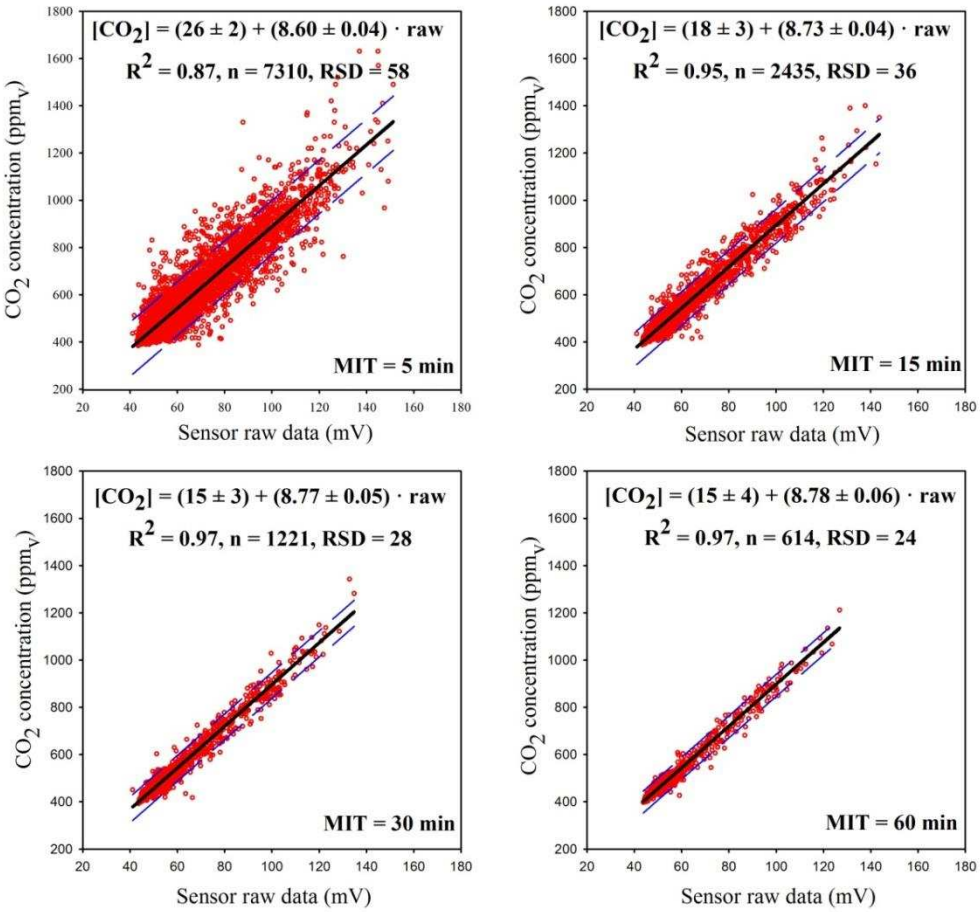


Figure 3. Relationship of $CO_2$ concentrations ([$CO_2$]) measured with the PAS analyzer and raw data (mV) from the NDIR sensors, at different mean integration times. The dashed blue lines represent the 95% confidence band.

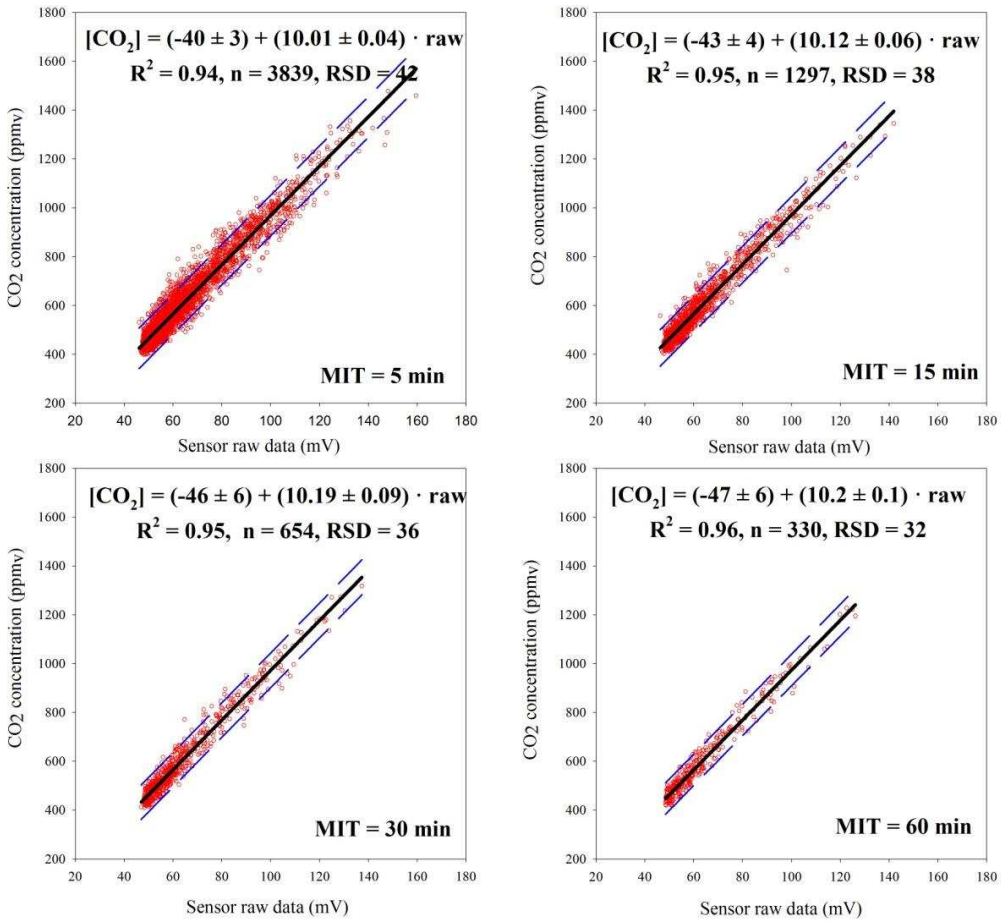


Figure 4. Relationship of $CO_2$ concentrations ([$CO_2$], $ppm_v$) measured with the OP-laser and averaged raw data (mV) from five NDIR sensors at different mean integration times (MIT, min). The dashed blue lines represent the 95% confidence band.

## Analysis of agreement between laboratory and field developed calibration equations

A Bland-Altman plot for $CO_2$ concentrations determined with the laboratory calibration method against $CO_2$ concentrations determined with the field developed calibration method with the PAS analyzers is presented in figure 5, for every tested MIT. The performed analysis of agreement is recommended by Altman & Bland (1983) for being a powerful tool of comparison between two measurement methods, and highlights the existence of systematic heterogeneous or homogeneous bias associated with the test method.

It can be seen from the plots in figure 5 that for all MITs, the majority of the data points are above the line of diff[$CO_2$] = 0, suggesting that the NDIR sensors tended to overestimate $CO_2$ concentrations compared to the PAS analyzer. This outcome might

have stemmed from the use of increasing MIT and distinct sampling mechanisms between the NDIR sensors and the PAS analyzers and will be further discussed later in this paper.

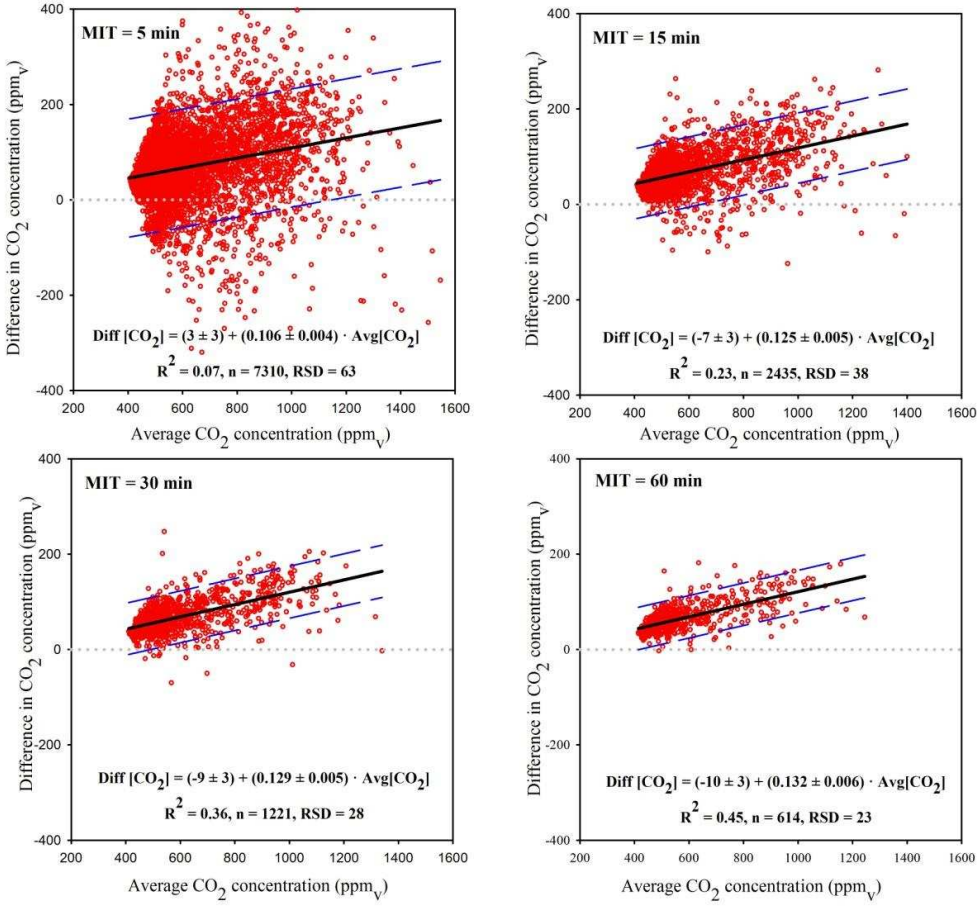


Figure 5. Bland-Altman charts for the relationship of $CO_2$ concentration determined through field calibration with the PAS analyzer and the laboratory calibrated NDIR sensors, at different mean integration times (MIT). The concentrations in X-axis are obtained by averaging out values obtained from field and laboratory calibrations. The dashed blue lines represent the 95% confidence band.

The plots presented in figure 3 show heterogeneous patterns in the spread of the data points along the measurement range for all tested MITs. The significance test for $\beta_o$ in equation 2 revealed that the systematic homogeneous error tended to be more negative with increase of MIT ($p<0.0001$), and varied from (-10 ± 3) to (3 ± 3) $ppm_v$. None of the estimated $\beta_o$ was significantly different than zero, indicating that MIT is not a strong source of disagreement between methods. When varying MIT from 5 to 60 min, the absolute increase in the homogeneous bias is only 7 $ppm_v$, which is considered

small compared to the $CO_2$ concentrations that are usually measured in livestock houses such as the studied dairy cow house, and can thus be neglected.

Results of the significance test performed on the coefficient $\beta_1$ in equation 2 demonstrated that for all MITs a systematic positive heterogeneous bias was present in the measurements of $CO_2$ concentrations made with the NDIR sensors in relation to the PAS analyzers, and varied between (0.106 ± 0.004) $ppm_v$ $ppm_v^{-1}$ to (0.132 ± 0.006) $ppm_v$ $ppm_v^{-1}$, or, 10.6 to 13.2% (figure 5). A positive heterogeneous (or proportional) bias indicates that as the mean $CO_2$ concentration in the dairy cow house became higher, the difference between concentrations measured with the NDIR sensors and PAS analyzers also enlarged. Christensen (1990) and USEPA (1998) have reported that cross interference between gaseous $CO_2$ and water vapor measured with IR-based techniques is a well-known phenomenon and needs to be taken into account, especially in livestock buildings where concentrations of $CO_2$ and water vapor are correlated (Zhao et al., 2012). However, Figure 6 shows that increasing $T_{dp}$ does not result in higher average values for the discrepancy between $CO_2$ concentration measurements from NDIR and PAS; instead, the average discrepancy remains constant as $T_{dp}$ increases, and cannot be used to explain the positive homogenous systematic error observed in the comparison between calibration methods with PAS and NDIR sensors.

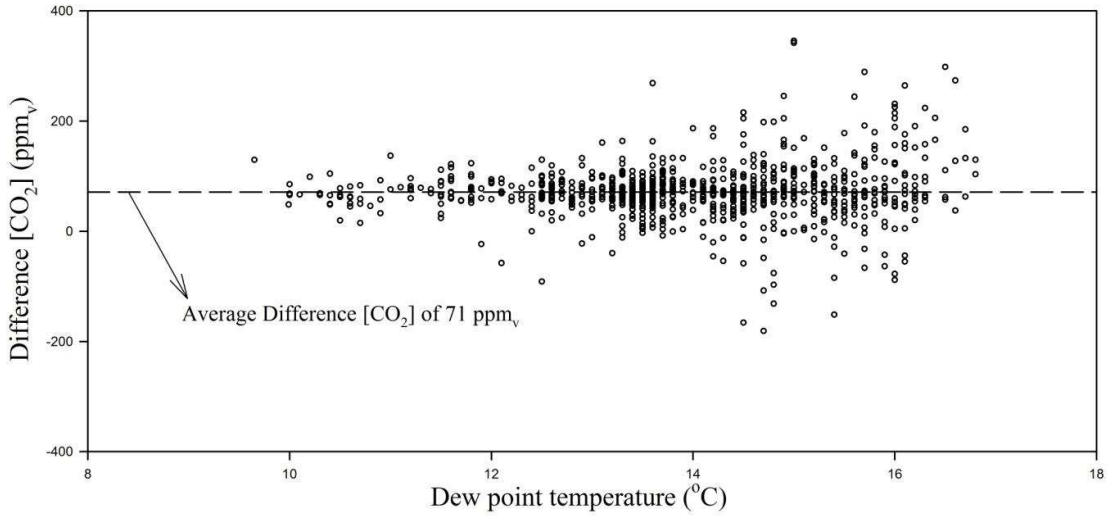


Figure 6. Plot representing the change in absolute difference between PAS and NDIR measurements of $CO_2$ concentrations ($ppm_v$) in the dairy cow house with increasing dew-point temperature ($T_{dp}$, $^oC$).

It is speculated that the positive heterogeneous bias observed in figure 5 might have stemmed not from the NDIR sensors, but from the PAS analyzer itself, through its internal cross interference with water vapor mechanism. Hassouna et al. (2013) have indicated that at higher air $T_{dp}$ values, the cross interference compensation of the PAS becomes crucial, and whether this mechanism is properly set by the PAS manufacturer has become a contentious matter in current literature body (Besson, 2006).

When looking at the effect of different MITs in the systematic heterogeneous bias, the values for $\beta_1$ presented in figure 4 suggest that an increase in MIT from 5 min to 60 min leads to increased systematic proportional overestimation of the $CO_2$ concentrations of 2.65%, which is considered small. The use of NDIR sensors with small MIT values, such as 5 min may be used, for instance, in behavioral studies that aim to catch the dynamics of change of $CO_2$ concentrations during feeding, resting, rumination and sleeping phases, for individuals or groups of animals. On the other hand, NDIR sensors adjusted with relatively large MIT values, such as 30 or 60 min may be used in emission studies for calculations of building VR based on the $CO_2$ mass balance method.

The results of the analysis of agreement between the laboratory calibration method and field calibration method with the OP-laser are presented in figure 7, for different MITs. At a given MIT, it can be seen from the plots in figure 7 that the data points presented a good distribution around the line of diff[$CO_2$] = 0. The significance test for $\beta_o$ in equation 2 revealed that it was different than zero at a significance level of 95% for all MITs, and varied between (57 ± 3) to (60 ± 9) $ppm_v$. These results support the existence of a systematic positive homogeneous bias (or overestimation) of the $CO_2$ concentrations made with the laboratory calibrated NDIR sensors in relation to the field calibration against the OP-laser.

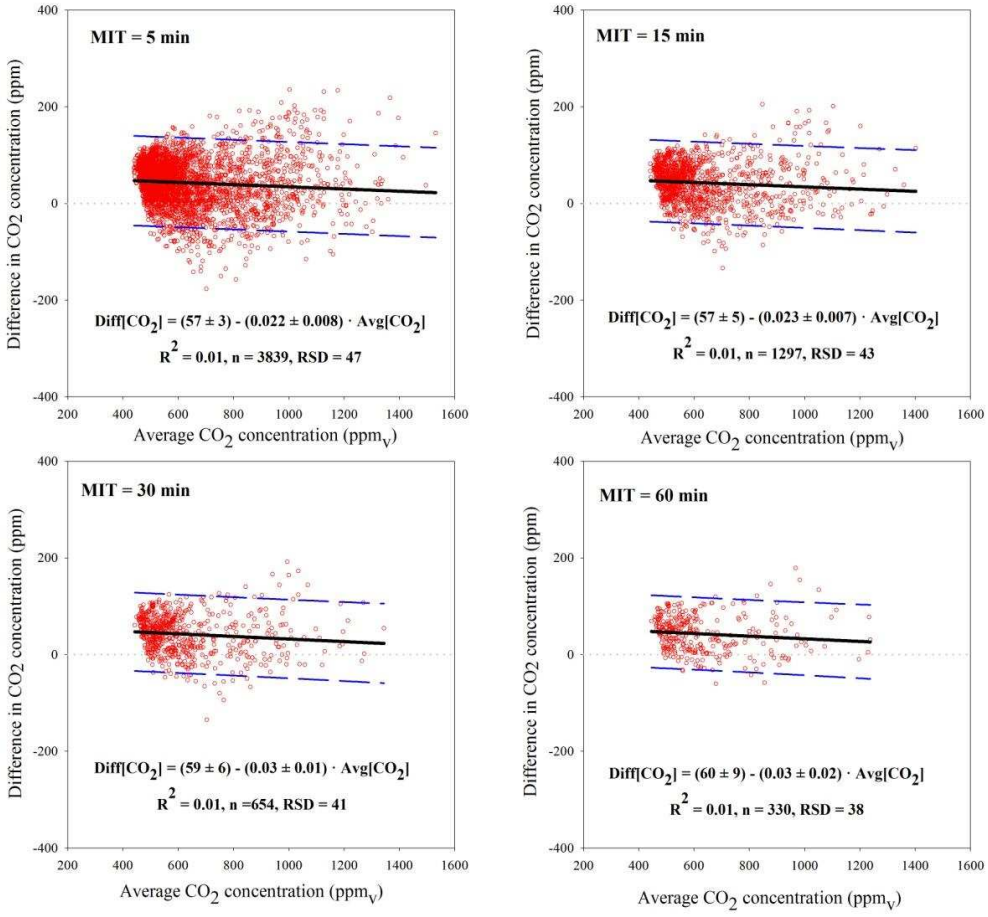


Figure 7. Bland-Altman charts for the relationship of $CO_2$ concentration determined through field calibration with the OP-laser and the laboratory calibrated NDIR sensors, at different mean integration times (MIT). The concentrations in X - axis are obtained by averaging out values obtained from field and laboratory calibrations. The dashed blue lines represent the 95% confidence band.

Daly & Bourke (2000) explained that systematic homogeneous data between two compared methods might be due to slight differences in the principle of each method. In this study, NDIR and OP-laser are distinct techniques for analyzing $CO_2$ concentration in air, giving different absolute values for the same air sample, but the trends in measurements were essentially the same. Chagunda & Yan (2011) when comparing a NDIR device to a OP-laser analyzer for measurements of methane ($CH_4$) concentrations from cattle, also observed that the NDIR method systematically overestimated the OP-laser method by 30 $ppm_v$, and related that discrepancy to inherent distinct nature of the measurement devices. Chagunda & Yan (2011) added that

although different methods resulted in concentrations that were distinct in absolute values, the trends in the measurements were similar.

Another potential source of overestimation of NDIR sensors, when calibrated in the laboratory, might be the sampling strategy used to compare both methods. Although every effort was in order to make the NDIR sensors capture the same concentrations as the OP-laser, such a task might be difficult to achieve given the inherent spatial variability of $CO_2$ concentrations present within NV livestock barns. For instance, the OP-laser measures an average concentration along a continuous path across the barn, while the average $CO_2$ concentration from the NDIR is obtained by 5 discrete points. In the case of this study, three NDIR sensors were placed above the milking cows zone which houses more cows, while only one sensor was placed over the dry and pregnant cows zone, which has a smaller number of animals per space allocated. Hence, this unbalanced distribution of NDIR sensors across the barn central axis might have, favoring the milking cows zone might have forced the average $CO_2$ concentration from the NDIR to go higher. This issue can be addressed by testing the effect of using different numbers of NDIR sensors and compare average values with the OP-laser data. Such analysis was done for a number of sensors equal or less than five, and the results can be found as Attachment 1. However, we did not compare the OP-laser with an average obtained from more than 5 NDIR sensors, which may be the focus of future research.

Results of the significance test performed on the coefficient $\beta_1$ in equation 2 demonstrated, for a given MIT, that a systematic proportional underestimation (or heterogeneous bias) of the $CO_2$ concentrations measured in the dairy cow barn with the laboratory calibrated NDIR sensors in relation to the field calibration with the OP-laser. The estimated values for $\beta_1$ varied from (-0.03 ± 0.02) to (-0.0022 ± 0.008) $ppm_v$ $ppm_v^{-1}$, and were not significantly different from zero at the level of 95% confidence. The effect of different MIT on $CO_2$ concentrations measured with laboratory calibrated NDIR sensors as compared to the field calibration with the OP-laser on homogeneous or heterogeneous biases was rather small, indicating that the use of different MIT did not adversely affect the agreement between both methods.

**Field application of the different calibration methods and analysis of uncertainty**

The laboratory and field developed calibration equations were applied to NDIR sensors' raw data collected during exposure to $CO_2$ concentration in the dairy caw barn

throughout the validation trial. The patterns of $CO_2$ concentrations calculated from sensors' raw data and those simultaneously measured with the PAS and OP-laser are presented in figure 8.

In figure 8 (top), one can see that field developed calibration equation yielded $CO_2$ concentration measurements that were closer to the values measured by the PAS analyzers, than those measured by the laboratory developed calibration equation. A similar result can be seen in figure 8-bottom, that using the field developed calibration equation with the OP-laser, with $CO_2$ concentrations closer to those measured by the OP-laser itself. These results indicate that the field calibrated NDIR sensors were capable to reproduce the concentrations measured by the PAS and OP-laser, by not showing any drift. One possible explanation for this outcome is that the field calibration include many other uncontrolled factors that are not possible to be reproduced in the lab during field calibration. The estimated NRMSE values for the field calibrated NDIR sensors are 7% and 8% when compared with the PAS and OP-laser, respectively (table 2).

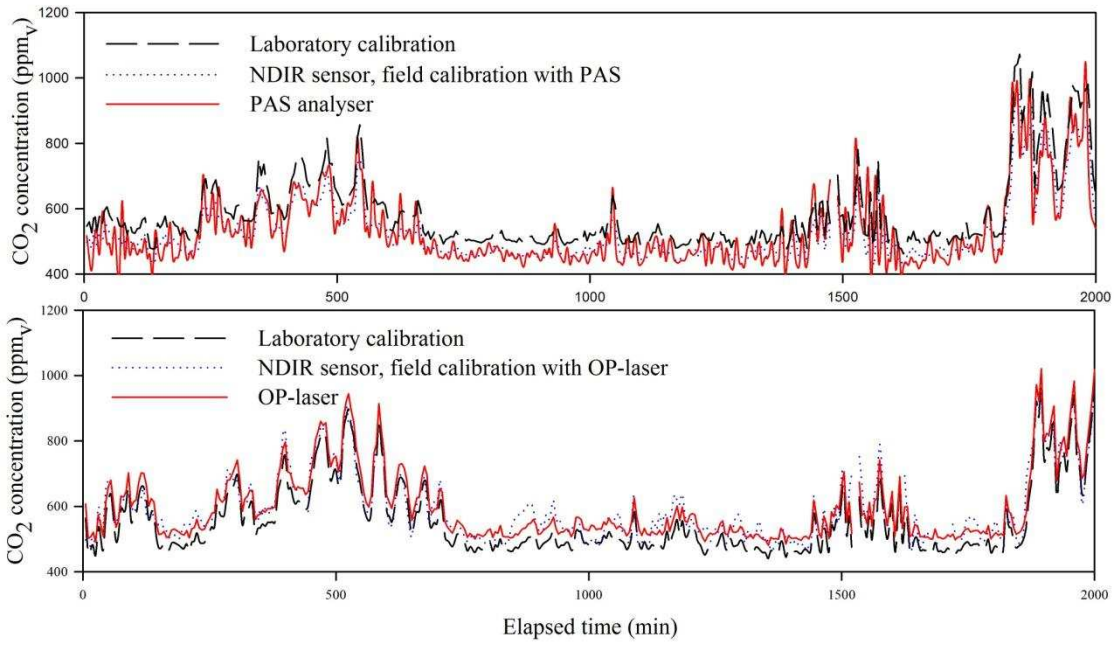


Figure 8. Field validation of the NDIR sensors for measurements of $CO_2$ concentrations in the dairy cow when single-point calibrated with the PAS analyzer (top); and when calibrated to measure the mean concentration in an open-path of 64 m in the cow barn with five sensors and the OP-laser for (bottom), both cases for a mean integration time (MIT) of 5 min.

Table 2. Summary of the comparison between field and laboratory calibrated NDIR sensors with the standard methods, PAS and OP-laser.

| Type of calibration method | Standard method | Difference between methods (mean ± $SE_{mean}$), $ppm_v$ | NRMSE*, % |
|---|---|---|---|
| Laboratory | PAS | 67 ± 1 | 13 |
| Field w/ PAS | PAS | 2± 1 | 7 |
| Laboratory | OP-laser | -23 ± 2 | 8 |
| Field w/ OP-laser | OP-laser | 20 ± 2 | 7 |

* Normalized Estimated Root Mean Square Error.

On the other hand, the relative better agreement between field calibrated sensors and the standard methods PAS and OP-laser seen in figure 8, is related to the fact that the conditions in which the validation trial was performed were similar to those of the calibration trials. The agreement might not have been the same if the validation was performed in a different farm, different season or with different PAS or OP-lasers. The use of laboratory calibrated NDIR sensors, in its turn, yielded in NRMSEs of 13% and 8%, when compared to the PAS and OP-laser, respectively (table 2), and support the fact that the laboratory calibration method is also appropriate.

Although the laboratory calibration and the field calibration (with PAS and OP-laser) methods presented biases as evidence of some disagreement between them, the results presented above indicate that none of the calibration procedures can be considered absolutely better than the other. Hence, despite the observed differences between $CO_2$ measuring devices and between calibration methodologies, the results of this study support that the NDIR $CO_2$ sensors are just as a feasible as the PAS and OP-laser for use in NV livestock barns.

## Conclusions

A Non-Dispersive Infra-Red (NDIR) sensor was tested for monitoring of carbon dioxide ($CO_2$) in a naturally ventilated (NV) dairy cow barn. Laboratory tests of linearity and sensitivity to static pressure were performed on the sensor. Single-point and open-path field calibration equations with a Photo Acoustic Spectroscopic (PAS) analyzer and an Open-Path laser (OP-laser), respectively, were developed for four distinct sensors raw mean integration times (MIT). The evaluation of agreement between tested and standard methods, and an analysis of uncertainty was performed on the field developed calibration equations. The following conclusions were drawn:

1. The tested NDIR sensor is a feasible alternative to monitor single-point or averaged spatial $CO_2$ concentrations in livestock barns by presenting a small variability between sensors of 5%, a sensitivity to static pressure of 0.08% of the reading per each 1hPa, and yields field measurements with an average uncertainty of 9 %;
2. Field or laboratory calibrated NDIR $CO_2$ sensors for multi-point monitoring of $CO_2$ concentrations in NV livestock barns are preferred, and can be as reliable as the PAS and the OP-laser methods;
3. The effect of averaging out $CO_2$ concentration measurements from NDIR sensors in MITs of 5, 15, 30 or 60 min was negligible.

## Acknowledgements

This project was financed by the Dutch Ministry of Economic Affairs and the Dutch Dairy Board within the Program "Duurzame Zuivelketen" (Sustainable Dairy Chain).

The authors would also like to acknowledge the Brazilian government funding agencies: CNPq (Portuguese acronym for National Council for Scientific Research and Development) and CAPES (Portuguese acronym for Council for Improvement of Highly Educated Personnel) for supporting researchers.

Gratitude is acknowledged to Mr. Johan Ploegaert and Mr. Jos Huis in ´t Veld from the Wageningen UR Livestock Research Institute for their great contribution to experiment setup, data collection and monitoring system maintenance.

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# CHAPTER 3. SPATIAL VARIABILITY OF MIXING RATIOS OF AMMONIA AND TRACER GASES IN A NATURALLY VENTILATED DAIRY COW BARN

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A manuscript submitted to the Journal Biosystems Engineering

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## Abstract

The use of the tracer gas method to estimate gaseous emissions from naturally ventilated (NV) livestock barns excludes the need of monitoring barn ventilation rate, which can be a laborious task in these kinds of buildings. Instead, it requires accurate measurement of the tracer release rate ($Q_T$) and a representative estimate of the mixing ratio between pollutant (P) and tracer (T) gases ($\overline{[P]/[T]}$). While the quality of $Q_T$ simply depends on using a commercial mass flow controller that is accurate enough, the

determination of a representative mixing ratio $\overline{[P]/[T]}$ is not a trivial matter, since the NV livestock barn airspace presents complex air motion patterns properties that might be dependent on barn spatial vertical (V) and cross horizontal (HC) dimensions. Hence, the goal of this study was to assess the spatial variability of concentrations of the artificial tracer gas sulfur hexafluoride ($SF_6$), the natural tracer carbon dioxide ($CO_2$) and the pollutant ammonia ($NH_3$), along with their mixing ratios ($[NH_3]/[CO_2]$, $[NH_3]/[SF_6]$, $[CO_2]/[SF_6]$), inside a naturally ventilated dairy cow barn. The results indicated that the vertical variability of the calculated mixing ratios became more stable with increase in height, reaching approximately constant values above the Animal Occupied Zone (AOZ, V > 2 m). Using both the naturally produced $CO_2$ and the artificially injected $SF_6$ as a tracer gas led to a homogeneous spread in behavior of mixing ratios along V and HC directions. Finally, the possibility of finding a zone within the barn airspace where mixing ratios are considered to be representative for the barn, and the implications of applying artificial or natural tracers are discussed.

**Keywords:** sampling strategy, tracer gas method, livestock barns, animal occupied zone, natural and artificial tracers.

## Introduction

Ammonia ($NH_3$) emissions from animal confinements have been the focus of research around the world for many years. The most important agricultural sources of this pollutant are cattle housing systems (Dentener & Crutzen, 1994; Bouwman et al., 1997; Ferm, 1998; Groot Koerkamp et al., 1998; Galloway & Cowling, 2002; Erisman et al., 2007), where dairy cattle housing systems are mainly naturally ventilated (NV).

It is widely acknowledged that the quantification of emissions from NV buildings is a far more complicated and challenging of a task than quantification of emissions from mechanically ventilated (MV) buildings, given the existing difficulties to accurately determine airflow rates (Scholtens et al., 2004). Considering the importance of NV buildings for cattle and other animal categories in many climate zones, a thorough understanding of their emission characteristics and potential mitigation options is highly relevant and requires a stronger methodological basis than currently available (Ogink et al., 2013).

According to Calvet et al. (2013), Ogink et al. (2013) and Takai et al. (2013), the tracer gas method has been considered a prominent candidate for the determination of flow rates and emissions from NV livestock buildings. Tracer gas studies are reported extensively in the contemporary literature dealing with residential, institutional (Furtaw Jr. et al., 1996; Eklund, 1999; Santamouris et al., 2008; Lim et al., 2010; Han et al., 2011; Xu et al., 2013) and agricultural systems (Demmers et al., 1998; Baptista et al., 1999; Kaharabata et al., 2000; Demmers et al., 2001; Snell et al., 2003; Van Buggenhout et al., 2009; Samer et al., 2011a; Samer et al., 2011b; Samer et al., 2012; Schrade et al., 2012; Shen et al., 2012; Wu et al., 2012; Kiwan et al., 2013; Samer et al., 2013; Shen et al., 2013a; Shen et al., 2013b).

The theoretical foundation for tracer gas research is provided by the mixing-dilution first degree differential equation described by Barber & Ogilvie (1982) (see demonstration in Attachment II), who indicated that for a given pollutant gas P and a tracer T, the pollutant's emission rate ($Q_P$) can be calculated as the product between the known injection rate of T ($Q_T$) and the ratio between concentrations of P ([P]) and T ([T]), both corrected for background, $\left(\overline{[P]/[T]}\right)$. In other words, when using the tracer gas technique the complicated task of determining building ventilation rate in calculating gaseous emissions is suppressed. Instead, obtaining a mixing ratio $\overline{[P]/[T]}$ representative for the entire barn becomes essential.

The premise that both P and T present similar mixing behavior in the region where the concentrations are to be measured might not be true when P and T have different physical properties, such as highly discrepant molecular masses. Such discrepancies especially take effect when the mixing conditions are not ideal. Furthermore, an ideal T is the one that leads to mixing ratios that present constant values at least in some region of the barn ventilated airspace, indicating thorough homogeneous mixing. Also, it is of importance for representative mixing ratios that the release method of T sufficiently mimics the release of P. Several tracers have been used in past research studies, e.g. the carbon dioxide ($CO_2$) naturally produced by the animals and stored manure (Xin et al., 2009; Samer et al., 2011b; Mosquera et al., 2012); and artificially injected tracers such as krypton-85 ($^{85}Kr$) (Samer et al., 2011a; Samer et al., 2011c; Kiwan et al., 2013), trifluoromethyl sulfur pentafluoride ($SF_5CF_3$)(Schrade et al., 2012), and sulfur hexafluoride ($SF_6$) (Kaharabata et al., 2000; Grainger et al., 2007;

Schrade et al., 2012; Wu et al., 2012; Lassey, 2013). However, a few studies have shown that not all chosen tracers, for instance $^{85}Kr$, behave the same when used for simultaneous determination of pollutant emissions from a ventilated airspace (Samer et al., 2012; Kiwan et al., 2013), and will lead to highly discrepant mixing ratio values. The risk on discrepancies will increase with NV barns that have a very open design with large air exchange openings (Ogink et al., 2013).

Hence, the goal of this study was to assess the spatial variability of concentrations of the pollutant $NH_3$ and the tracer gases $CO_2$ and $SF_6$, along with their ratios ($[NH_3]/[CO_2]$, $[NH_3]/[SF_6]$, and $[CO_2]/[SF_6]$), inside a NV dairy cow barn. Specific objectives were (a) to delineate potential differences in distribution and mixing patters between the tracers $SF_6$ and $CO_2$ and (b) to determine whether it is possible to find a zone within the barn airspace where representative $\overline{[P]/[T]}$ mixing ratios can be measured.

## Methodology

A selected dairy cow barn was equipped with an injection system for controlled release of $SF_6$. Two sampling poles were installed in the dairy cow barn, with the goal of monitoring the patterns in dispersion of the pollutant $NH_3$ and the tracers $CO_2$ and $SF_6$ in the vertical direction and in the horizontal cross barn direction. A more thorough description of barn and $SF_6$injection system, experimental procedures and data analysis is provided below.

### Description of the dairy cow barn and animals management

This study took place in a NV dairy cow barn (figure 1) with a design that is representative for modern dairy barns in Northern Europe. The barn was located in Bunschoten, in the middle of the Netherlands, is east-west oriented, a roof with 37% slope, and has dimensions of 64 Length × 38 Width × 4 Side wall Height m (L × W × H). The building envelope is composed of insulated roof and open side walls, the lateral openings on both sides are 2.75 m high, protected with stainless steel screens with openings of 5 × 5 cm and has manually operated curtains. In the eastern part of the building there is a deep litter area of 10L × 21W m with maximum housing capacity of 25 dry and pregnant cows. In the central part of the building, 3 double-rows of cubicles (paper chips bedding; 42L × 21W m) are located, with feeding alleys on both sides

(north and south), and maximum housing capacity for 150 lactating cows. The last section of the barn is at the most western side, has an area of 13L × 21W m with similar cubicles and bedding system as for the lactating cows, where the heifers are kept (maximum capacity of 40 heifers). Barn cubicles area had concrete slatted walking alleys and an automatic scraping robot. Manure is stored in a deep pit space of 65L × 21W × 2D m located under the slats and cubicles. The lactating cows had free access to 3 milking robot systems. All cows were kept inside all year long and were fed with roughage (grass and corn silage) and additional concentrates. The data collection and validation trials in the barn were conducted during the summer season, in the months of June, July and August of 2012.

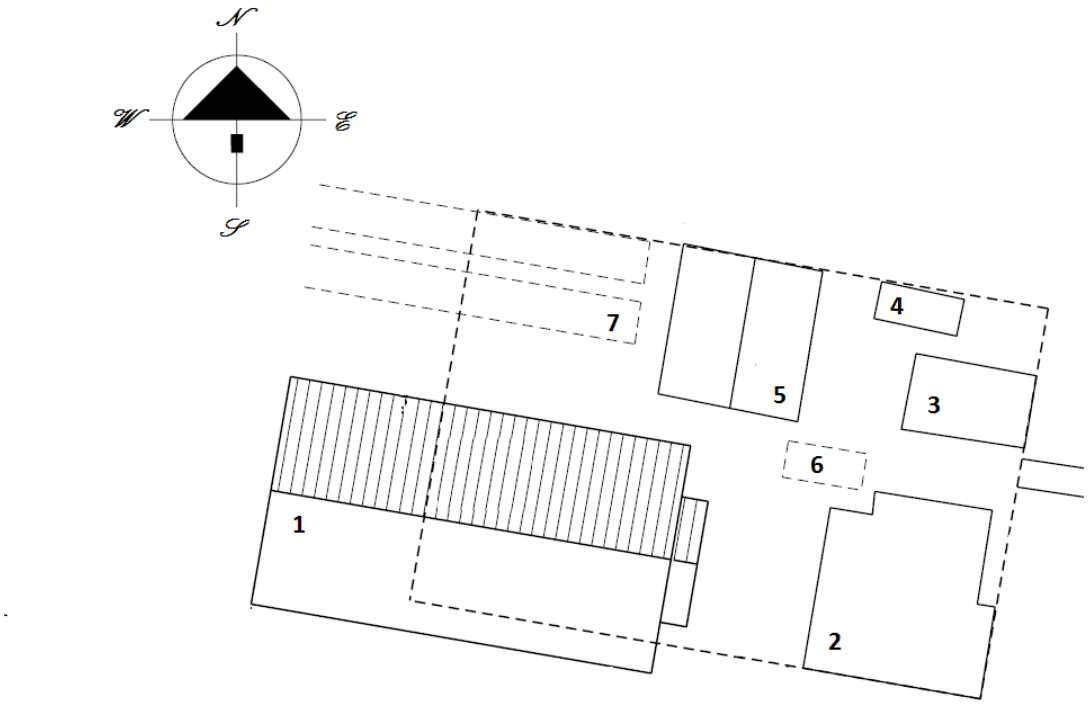


Figure 1. Farm site layout and description (right): 1- dairy cow barn; 2– young cattle barn; 3- farmer´s house; 4- storage; 5- machine shed; 6 and 7- silos.

### Description of the $SF_6$ injection system

The $SF_6$ injection system (figure 2) was designed to mimic the release of pollutant gases in the barn. Pure $SF_6$ (99.9%) tank and air compressor system were kept in a sheltered wagon placed outside near the western extremity of the barn. At a controlled

mass flow rate of 0.027 L $min^{-1}$ (GFM 57, Aalborg Instruments & Controls, Orangeburg, NY, U.S.A.), $SF_6$(@ 99.9%) was mixed with compressed air at a flow rate of 10 L $min^{-1}$ (GFM 57, Aalborg Instruments & Controls, Orangeburg, NY, U.S.A.), the air-$SF_6$ mixture was channeled to the barn through polyethylene (PE) tubing (0.63 cm inside diameter) where it was split into three branches (south, central and north). South and north branches were spread along both feeding fences. The central branch was spread along the cubicles area and beyond the milking parlor, with the injection points placed at approximately 0.5 m from the floor. A total of 116 injection points were distributed along the barn, including the lactating cows, dry cows and heifer'sarea.

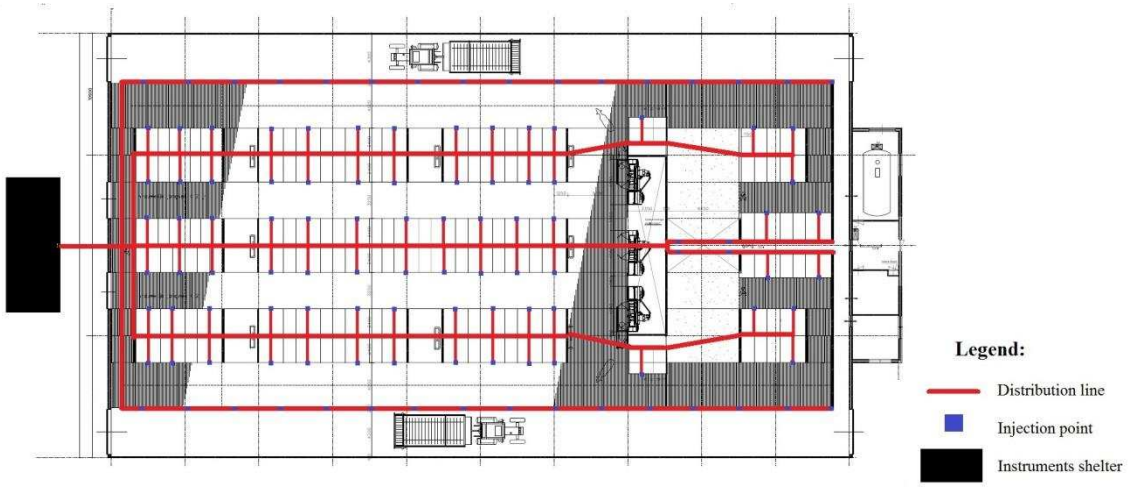


Figure 2. Drawing of the $SF_6$ distribution lines and injection points spread along the dairy cow barn.

**Vertical and horizontal cross barn variability of concentrations and mixing ratios**

Two sampling poles were designed to measure concentrations of $SF_6$, $CO_2$ and $NH_3$ at 4 different vertical distances from the slats (V = 1, 2, 3 and 4 m from the floor) in two different locations (North and South cubicle alleys) along the width of the barn. Location South was 20 m west from the milking parlor, 11 m from the south side wall and location North was also placed 20 m west from the milking parlor, but 11 m from the north wall (figure 3).

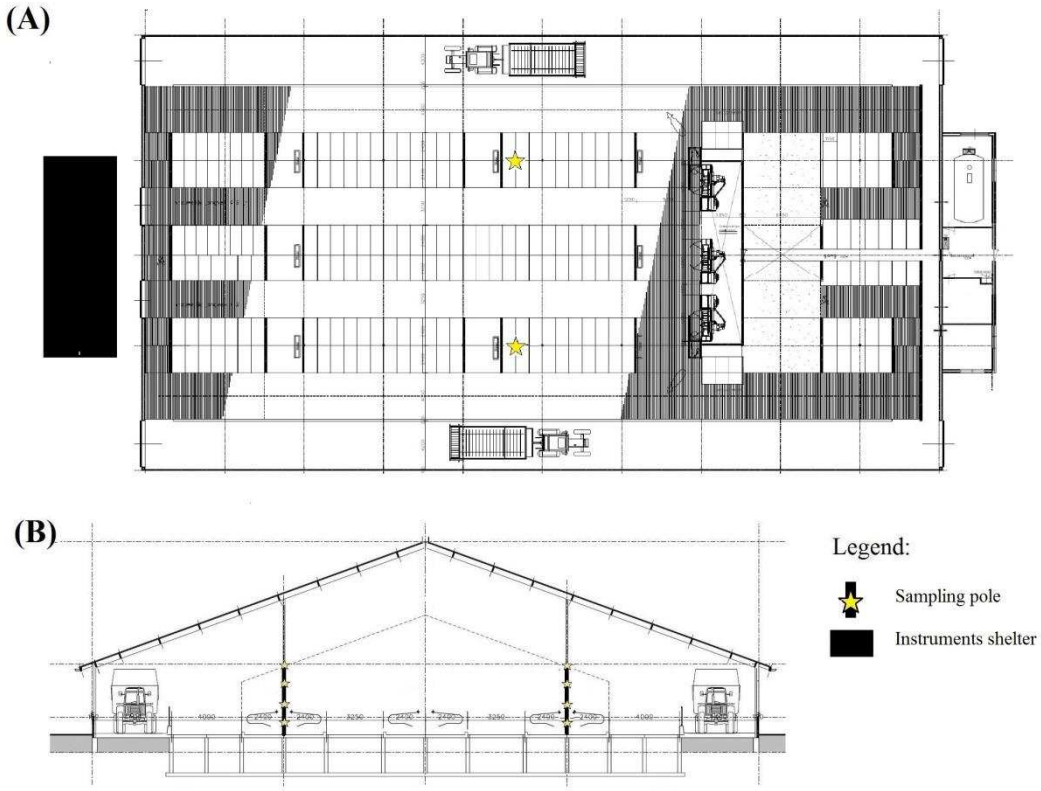


Figure 3.Top (A) and transversal (B) view cuts of the investigated barn with the allocation of the poles for sampling of carbon dioxide ($CO_2$), sulfur hexafluoride ($SF_6$) and ammonia ($NH_3$) aerial concentrations (not to scale).

For each location, two sampling lines (Teflon® tubing, 0.63 cm inside diameter) were used to collect simultaneous air samples at every height (total of 8 sampling points per location); the sampling lines were supported by a 4 m (height) stainless steel pole (figure 4-A). One of the sampling lines coming for every height was connected to a Tedlar® bag (maximum volume of 20 L), which was connected to a vacuum pump at a flow rate of 400 mL $min^{-1}$. The other sampling line coming from every height was plugged into one impinger train. Each train consisted of three Greenburg-Smith® type impingers connected in series with leak-free ground glass fittings and Teflon tubing. The first and second impingers contained each 125 mL of 0.1 N sulfuric acid ($H_2SO_4$) and the third was empty to collect excess acid solution potentially coming from the adjacent impingers. A vacuum pump (1000 mL $min^{-1}$) was connected to each impinger train. Hence, each monitoring station consisted of 4 impinger trains, 4 Tedlar bags and four vacuum pumps (figure 4-B).

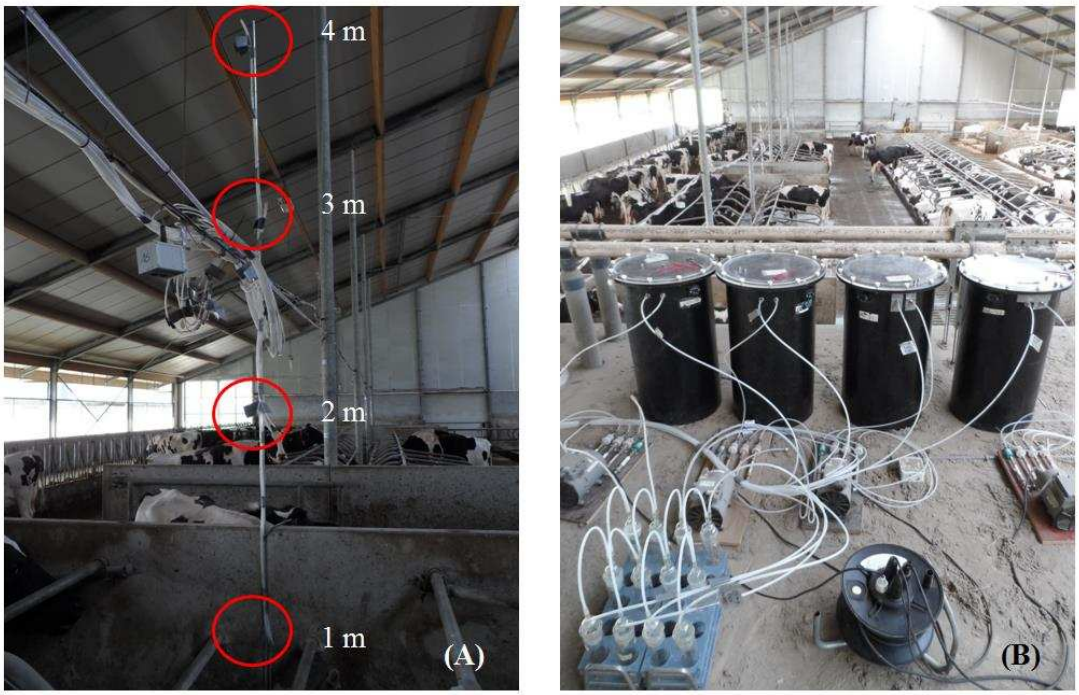


Figure 4. Pictorial representation of a gaseous sampling poles (A), with highlights for the sampling ports at different heights; and a monitoring station (B), presenting the containers with Tedlar® bags, impingers´ train and air pumps.

During each measurement period, all pumps were turned on for approximately 120 min. After the measuring period, both the Tedlar® bags and impinges were sent to the laboratory for analysis of gaseous concentrations of $CO_2$ and $SF_6$ through the gas chromatography (GC) method, while the impingers were analyzed for ammonium-N content (mg $L^{-1}$). Additional meteorological conditions of wind speed and direction were measured with transmitter (AMES, model VMT 107A, Brezovica, Slovenia; accuracy of ± 0.5 m $s^{-1}$ for speed and ± 5$^{o}$ for direction) and a temperature and relative humidity sensor (HMP45A/D, Vaisala, Woburn, Mass, USA; accuracy of ± 0.01 $^{o}$C for temperature and ± 3% for relative humidity). Data on wind speed, direction environmental temperature and relative humidity were monitored at every 15 min.

**Data processing and statistical analyses**

A total of 7 trials of 120 min duration each were performed in the summer of 2012. Prior to every monitoring campaign, barn screens were closed to 50% on both sides, resulting in an effective opening area of 92 $m^2$ per side. The $SF_6$ injection system

was turned on at least 30 min before measurements started to allow full stabilization of concentrations in the barn envelope.

Before the data analysis procedures, data sets collected with the sampling poles from each side of the barn (north and south) were combined with wind direction, based on which inlet and outlet sides were defined, thus, data sets collected from north and south poles were denominated "near inlet" or "near outlet" depending on the wind direction.

An analysis of variance (ANOVA) was performed with the factors vertical component (V: 1, 2, 3 and 4 m from slats) and the cross horizontal component (HC, near inlet or outlet) with the response variable being gaseous concentration of pollutant and tracer gases and the mixing ratio between both. The analysis was done through the procedure GLM in SAS® to test if the data can be explained by a model with the shape in equation 1. Pairwise test comparison between every level of V and HC was also implemented with the statistical model by adding the statement pdiff in the SAS® code. All tests were performed on a significance level of 0.05.

$$Y = \beta_0 + \beta_1 \cdot V + \beta_2 \cdot HC + \varepsilon_i \quad (1)$$

Where:

Y – pollutant or tracer gaseous concentration, or ratio between pollutant and tracer;

V – vertical dimension of the barn, or height from slats(1, 2, 3 or 4 m);

HC – cross horizontal barn dimension, or building width (near inlet or outlet);

$ß_0$, $ß_1$ and $ß_2$ – empirical model coefficients obtained from ANOVA;

$\varepsilon_i$ - independent normally distributed homogeneous random error.

When the statistical analysis was performed with data at the concentration level, the data was used as-is. However, when analysis was done with mixing ratios of the monitored of P and T, their gaseous concentrations were corrected for the constant background values of 0.13 $ppm_v$, 417 $ppm_v$ and 0 $ppb_v$, for $NH_3$, $CO_2$ and $SF_6$ respectively.

## Results and discussion

A summary of cow number and meteorological conditions inside and outside the barn, along with sidewall air inlet position data at each trial are presented in table 1. It can be seen that during most of the periods, the wind was coming mainly from the north, being the north sidewall considered the predominant air inlet.

Table 1. Characteristics of the housed dairy cows and climate conditions during trials

| | Trial | | | | | | |
|---|---|---|---|---|---|---|---|
| **Variable** | **1** | **2** | **3** | **4** | **5** | **6** | **7** |
| Number of milking cows | 140 | 135 | 136 | 134 | 135 | 142 | 144 |
| Number of dry cows | 22 | 25 | 24 | 29 | 28 | 21 | 22 |
| Number of pregnant young cows | 33 | 33 | 33 | 31 | 31 | 34 | 35 |
| Milking cows live weight (kg) | 664 | 663 | 663 | 661 | 660 | 662 | 658 |
| Dry cows live weight (kg) | 664 | 663 | 663 | 661 | 660 | 662 | 658 |
| Pregnant young cows live weight (kg) | 500 | 500 | 500 | 500 | 500 | 500 | 500 |
| Milk production (kg/cow/day) | 30.1 | 30.7 | 30.6 | 30.4 | 30.6 | 30.6 | 27.6 |
| Avg. inside air temperature (ºC) | 20.4 ± 0.2 | 18.3 ± 0.1 | 19.0 ±0.2 | 25.6 ± 0.2 | 26.8 ± 0.3 | 19.9 ± 0.2 | 23.2 ± 0.1 |
| Avg. inside air relative humidity (%) | 77 ± 1 | 89 ± 1 | 79 ± 2 | 63 ± 2 | 79 ± 2 | 95 ± 1 | 68 ± 1 |
| Avg. outside air temperature (ºC) | 20.4 ± 0.2 | 16.3 ± 0.1 | 17.3 ±0.2 | 25.0 ± 0.4 | 25.4 ± 0.4 | 19.4 ± 0.3 | 22.3 ± 0.1 |
| Avg. outside air relative humidity (%) | 68 ± 1 | 83 ± 1 | 67 ± 1 | 57 ± 2 | 72 ± 2 | 98 ± 1 | 63 ± 1 |
| Mean wind speed (m $s^{-1}$) | 5.67±0.15 | 5.78±0.15 | 2.93±0.16 | 2.5±0.13 | 1.91±0.17 | 4.87±0.40 | 4.33±0.17 |
| Mean wind direction | SW | NW | NW | NE | NW | SE | SE |
| Sidewall considered as relative inlet | South | North | North | North | North | South | South |

### Spatial distribution analysis of gaseous concentrations

The V and HC distribution of gaseous concentrations of $NH_3$, $CO_2$ and $SF_6$ are plotted in figure 4. When looking at the vertical pattern of the measurements observed in figure 4, one notices that, in general, the concentrations tend to stabilize to a constant value from V ≥ 2 m. The Animal Occupied Zone (AOZ) in the barn that goes up to V < 2 m is generally characterized by turbulent air flow, lower wind speeds and thus poorer mixing as compared to upper levels, and might be the reason why some measurements in that zone presented a more unpredictable behavior. This is presumably due to the presence of the animals and building structures such as fences, walls, cubicle metal frames, etc., which act as obstacles to the air flow by reducing wind speed. The complexity of the AOZ in terms of air and gaseous flow pattern predictability was acknowledged by Bjerg et al. (2008) and Wu et al. (2012) when developing a computational model for air motion in NV dairy cow barns.

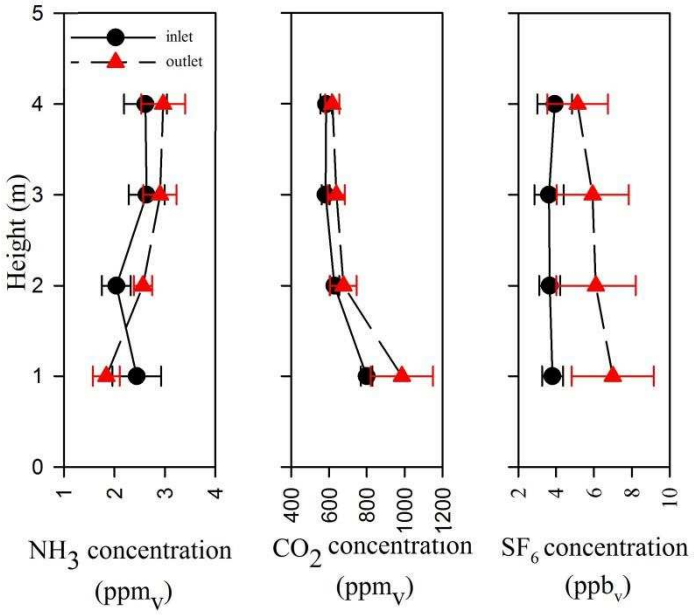


Figure 4.Vertical (height) and cross horizontal (near inlet or outlet) variability of concentrations of $NH_3$, $CO_2$ and $SF_6$ in the naturally ventilated dairy cow barn, the error bars correspond to standard error of the mean.

The results of the pairwise comparison analysis made for each monitored gas across heights is presented in table 2, and show that the differences in concentrations between distinct levels was higher when the pairwise comparison was done in relation to V = 1 m, with a more pronounced effect for the gas $CO_2$. This outcome might be due to the close proximity of the sampling points to the $CO_2$ emitting source. The small differences in relation to the comparisons involving V = 1 m indicates that outside the AOZ, gaseous concentrations of $NH_3$, $CO_2$ and $SF_6$ are not sensitive to height, and are approximately constant.

Table 2. Results of the pair-wise comparison test for heights. The numbers represent the absolute difference in concentration between the considered heights

| **Absolute height comparison (m)** | **$NH_3$ ($ppm_v$)** | **$CO_2$ ($ppm_v$)** | **$SF_6$ ($ppb_v$)** |
|---|---|---|---|
| 1 – 2 | 0.16 | 223 | 0.270 |
| 1 – 3 | 0.63 | 262* | 0.125 |
| 1 – 4 | 0.65 | 267* | 0.272 |
| 2 – 3 | 0.47 | 39 | 0.145 |
| 2 – 4 | 0.49 | 45 | 0.002 |
| 3 – 4 | 0.02 | 6 | 0.146 |

*mean difference is significantly different from zero at a significance level of 95%.

The HC distribution of the gases is represented by the concentrations that, at a certain height, were measured near barn inlet or outlet sides. It can be seen in figure 4 that for all gases, the concentrations measured near the outlet were slightly higher than those monitored near the inlet. This outcome evidences the existence of a cross air flow through the building, in which the fresher air entering at the inlet side opening purges the gases produced in the AOZ of the barn, leaving from the outlet side opening. This kind of flow is typical in NV barns and is mainly wind driven (Albright, 1990). However, the overlapping standard error bars at each level, indicate that differences between the concentrations measured near inlet and outlet could not be distinguished in statistical terms. As a matter of fact, the ANOVA results showed that for all monitored gases, the barn width factor didn´t have a significant effect on concentration measurement (p-values ranging from 0.11 – 0.60).

Additionally, for a specific height, the concentration measured near outlet was divided by that measured near inlet; the results of this ratio are graphically presented in figure 5 for the gases $NH_3$, $CO_2$ and $SF_6$.

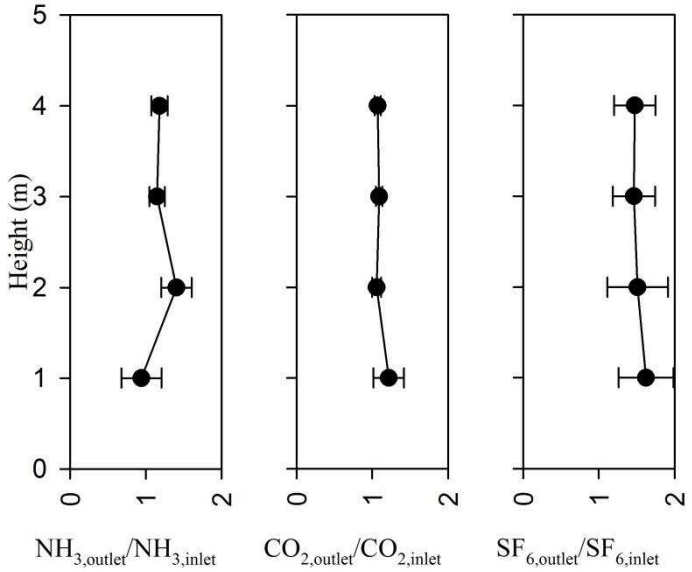


Figure 5.Vertical concentration ratios measured near inlet and outlet for the gases $NH_3$, $CO_2$ and $SF_6$, monitored in the naturally ventilated dairy cow barn, the error bars correspond to standard error of the mean.

The average values for inlet/outlet ratio calculated over t between V = 3 and V = 4 m, where mixing show more stable patterns (figure 4), were (1.2 ± 0.1), (1.08 ± 0.03)

and (1.5 ± 0.2) for the gases $NH_3$, $CO_2$ and $SF_6$, respectively. These ratios indicate that for $NH_3$ and $CO_2$, the increase in concentrations near the outlet is only 8 to 20% higher than that near the inlet, and that both $NH_3$ and $CO_2$ presented similar distribution patterns across barn width. However, for the gas $SF_6$, the concentration near outlet can be in average 50% higher than that at near the inlet. This means that the distribution of $SF_6$ across the barn width was not even, indicating a different behavior in spread. From figure 5, a similarity in distribution behavior of $NH_3$ and $CO_2$ can be deduced. Possible reasons for the poorer distribution of $SF_6$ across the barn might be the relatively higher molecular weight of $SF_6$ (146.06 g $mol^{-1}$), as compared to $CO_2$ (44.01 mg $mol^{-1}$) and $NH_3$ (17.03 g $mol^{-1}$), which might have caused it to present a different dispersion pattern, by remaining stagnated within the barn lower levels, while the other gases were able to rise and leave through the outlet. The positioning of the $SF_6$ injection lines might also have played an important role on the spread of that gas, by defining its release and dispersion patterns. This outcome highlights the need of evaluating the performance efficiency of complex artificial tracer injection systems, such as the one used in this study, prior to the start of monitoring periods, this might be a motivation for further research.

**Analysis of spatial distribution of pollutant and tracer mixing ratios**

The spatial variability of the mixing ratios $NH_3/CO_2$, $NH_3/SF_6$ and $CO_2/SF_6$ are graphically represented in figure 6 and the results of the pair-wise comparison between ratios calculated for different heights are presented in table 3. The ANOVA resultsindicated that the horizontal width dimension of the barn didn´t have a significant impact on the calculated mixing ratios (p-values ranging from 0.08 – 0.96).

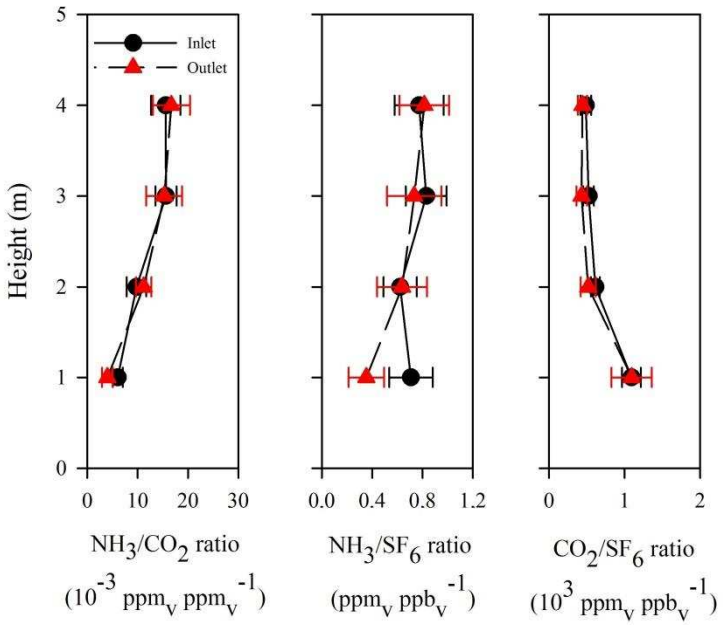


Figure 6.Vertical (height) and horizontal (near inlet or outlet) variability of the mixing ratios $NH_3/CO_2$, $NH_3/SF_6$ and $CO_2/SF_6$ in the naturally ventilated dairy cow barn, the error bars correspond to standard error of the mean.

The calculated mixing ratios involving $NH_3$ as pollutant, shown in figure 6, tended to present lower values within the AOZ and approximately constant values above it. Such results corroborates what was demonstrated before in this paper that the complex air flow patterns present in the AOZ makes it a risky place to determine gaseous concentrations and mixing ratios that are representative for the entire ventilated airspace, and should be avoided. The pair-wise comparison analysis output presented in table 3 for the mixing ratios $NH_3/CO_2$ and $NH_3/SF_6$ supports the fact that in the AOZ, the ratios were significantly lower than all the mean ratios calculated above it. Based on this outcome, it is possible that if mixing ratios are calculated with concentration data monitored within the AOZ, the averaged barn mixing ratio will be biased. Preference should be given to sampling strategies set to monitor regions within the barn where mixing ratios present relatively constant values.

Table 3. Results of the pair-wise comparison test for heights. The numbers represent the absolute difference in mixing ratios between the considered heights

| Absolute height comparison (m) | $NH_3/CO_2$ ($10^{-3}ppm_v\ ppm_v^{-1}$) | $NH_3/SF_6$ ($ppm_v\ ppb_v^{-1}$) | $SF_6/CO_2$ ($10^{-3}ppb_v\ ppm_v^{-1}$) | $CO_2/SF_6$ ($ppm_v\ ppb_v^{-1}$) |
|---|---|---|---|---|
| 1 – 2 | 5.20 | 0.246 | 7.78 | 0.282 |
| 1 – 3 | 10.13* | 0.543* | 11.42* | 0.203 |
| 1 – 4 | 10.50* | 0.444* | 13.21* | 0.353 |
| 2 – 3 | 4.93 | 0.298 | 3.64 | 0.078 |
| 2 – 4 | 5.93 | 0.198 | 5.42 | 0.071 |
| 3 – 4 | 0.37 | 0.099 | 1.79 | 0.150 |

*mean difference is significantly different than zero at a confidence level of 95%.

The presence of approximately constant mixing ratios between pollutant and tracer gases above the AOZ is an indication that both gases present similar mixing conditions, and hence, ratios measured at H > 2 m shall be used to estimate gaseous emissions of $NH_3$.

As for the comparison between mixing ratios near inlet vs. near outlet, it can be seen in figure 6 that above the AOZ, both mixing ratios $NH_3/CO_2$ and $NH_3/SF_6$ presented values near the inlet that were similar to those at the outlet. This result is corroborated by the pairwise test performed for the horizontal (near inlet and outlet) positions, resulting in ratios that were statistically the same. Such outcome is specifically true for the mixing ratio $NH_3/SF_6$, and indicates that even if at concentration level, $SF_6$ presented greater differences between near inlet and outlet positions than $NH_3$, as discussed before in this paper, the horizontal variability of their mixing ratios were similar. This result evidences the robustness of the mixing ratio method for estimating gaseous emissions from NV livestock barns, that P and T don´t necessarily need to be homogeneously spread in the barn to yield homogeneously spread mixing ratios. The pitfall here, however, is that if there are problems with the artificial injection system that lead, for instance, to leakage of T, they cannot be detected.

The hypothesis of the similar mixing conditions between pollutant and tracer gases tested in this study was proven to be valid outside the AOZ. On the other hand, the data presented in this paper indicated that when sampling of concentrations is done within the AOZ, the mixing ratios will present higher variability and may not be representative for the entire airspace.

Lastly, since gaseous mixing might be also dependent on curtains opening, and since in this study the curtains were kept constantly open at 50% on both sides, the

similar mixing conditions condition may not be valid at very open conditions. For this reason, it is recommended that the effect of different window openings, e.g. 75 and 100% both sides, on the spatial distribution of concentrations and mixing ratios be further investigated.

## Conclusions

A dairy cow barn was equipped with an injection system for controlled release of $SF_6$ and two sampling poles in order to monitor the patterns in vertical (V, 1 to 4 m above the slats) and cross horizontal barn (HC, near inlet and outlet) dispersion of the pollutant $NH_3$, the naturally present tracer $CO_2$, the artificially injected $SF_6$ and their mixing ratios. The following conclusions can be drawn:

1. The vertical variability of concentrations of $NH_3$, $CO_2$ and $SF_6$ and their mixing ratios became more stable with increase in height, reaching approximately constant values above the Animal Occupied Zone (AOZ, V > 2 m);
2. The cross horizontal barn spread of the naturally produced tracer $CO_2$ resembled more that of the pollutant $NH_3$, than the artificially injected tracer $SF_6$, as expressed by inlet/outlet concentration ratios.
3. The use of both, $CO_2$ and $SF_6$, as a tracer gas led to similar vertical and cross horizontal barn homogeneous spread in behavior of mixing ratios.
4. In the conditions of this study, the most appropriate region in the barn to measure the concentrations of $CO_2$, $SF_6$ and $NH_3$ and mixing ratios of $NH_3/CO_2$ and $NH_3/SF_6$, is above the AOZ (V > 2 m).

## Acknowledgements

This project was financed by the Dutch Ministry of Economic Affairs and the Dutch Dairy Board within the Program “Duurzame Zuivelketen” (Sustainable Dairy Chain).

The authors would also like to acknowledge the Brazilian government funding agencies: CNPq (Portuguese acronym for National Council for Scientific Research and Development) and CAPES (Portuguese acronym for Council for Improvement of Highly Educated Personnel) for supporting researchers.

Gratitude is acknowledged to Mr. Johan Ploegaert and Mr. Jos Huis in ´t Veld from the Wageningen UR Livestock Research Institute for their great contribution to experiment setup, data collection and monitoring system maintenance.

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# CHAPTER 4. AIR MOTION PATTERNS AND AIR EXCHANGE RATES OF A NATURALLY VENTILATED DAIRY BARN BY MEANS OF A CFD MODEL TESTED AGAINST THE CARBON DIOXIDE MASS BALANCE METHOD

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A manuscript submitted for *poster* presentation at the 2014 International Conference of Agricultural Engineering (AgEng 2014), in Zurick, Switzerland, 6 – 10 July, 2014

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## Abstract

The Computational Fluid Dynamics (CFD) is a powerful tool for studying the motion of air and target pollutants in naturally ventilated livestock barns. It can be used to calculate barn air and pollutants exchange rates on the condition that models are properly validated. Most CFD models include mainly and only, air as a working fluid and don´t take into consideration the generation and motion patterns of specific gases such as carbon dioxide ($CO_2$), which is directly linked to animals´ metabolic activity. Here, insight may improve measurement methods for air exchange rate based on tracer gas methods, such as the metabolically produced $CO_2$. Metabolic $CO_2$ production models can be integrated in CFD models to challenge modelled results with measured $CO_2$ concentrations and assess their combined prediction accuracy. This study was designed to assess the combined use of a CFD model and a metabolic $CO_2$ production model to predict air flows and $CO_2$ distribution in a naturally ventilated dairy cow barn. The studied naturally ventilated dairy cow barn is a free stall with slatted floors and manure storage below the slats. Its housing capacity is 136 dairy cows, 25 dry cows and 33 young pregnant cows, all kept inside year round. The lactating cows had free access to an automatic milking robot system and were fed with concentrate, and either fresh grass, maize silage or any combination of the latter, depending on season. The representation of the barn airspace in the computational domain was done with a mixed hexahedral dominant mesh. The animal occupied zone (AOZ) was represented as porous media meshes with porosities of 92, 96 and 93% for the milking, dry and young pregnant cows, respectively, coupled with the mesh representative of barn airspace. The porous media were implemented with heat and $CO_2$ generation equations mimicking animal activity, following CIGR (2002) specifications. The full paper being written on this of this CFD model will contain results of the comparison of the modeled $CO_2$ concentrations measured in the barn airspace with continuously monitored $CO_2$ concentration data collected in the dairy cow barn with a homogeneous grid of 15 Non-Dispersive Infrared (NDIR) sensors, installed on a horizontal plane 3 m above the slats. A calculated Normalized Mean Square Error (NMSE) of 0.053 indicated that the CFD model may be used to predict air motion and $CO_2$ dispersion accurately. Further development of the model will allow for calculation of pollutant emission rates in an hourly basis and as a function of external conditions such as variable wind speed and direction.

**Keywords:** Computational Fluid Dynamics, livestock barns, gaseous emission rate, mass and energy balance, metabolic $CO_2$ production

## Introduction

The dynamics of the air motion in naturally ventilated (NV) livestock barns is more complex than in mechanically ventilated buildings (Barber & Ogilvie, 1982), and that is in part due to aspects such as outside wind direction and intensity, air temperature (De Paepe et al., 2013); and in part to barn design characteristics such as inlet and outlet opening sizes (Bjerg et al., 2002), and presence of objects within the ventilated airspace that work as obstacles to free flow of air and gases (Svidt et al., 1998). However, understanding the movement behavior of air, the carrier fluid of target pollutants, in these kinds of buildings is a key element to understand pollutant release, dispersion and emission from the building.

One possible approach to unravel the motion patterns of the air and pollutants in NV livestock buildings would be to install a dense grid of sensors within the ventilated airspace and monitor pollutant concentrations, air speed and temperature in as many points as possible. While this is certainly doable, it is not feasible in most practical situations, due to limitations such as installation costs, maintenance and complexity of the required monitoring system (Bjerg et al., 2013). Another promising solution for the proposed problem is the use of Computational Fluid Dynamics (CFD), from which one can describe air movement models as realistic as possible, and when properly validated, may be used to understand pollutant pathways and ultimately emissions from NV livestock buildings (Arcidiacono & D´Emilio, 2006). CFD has been used successfully for ventilation modeling in rooms of commercial buildings (van Hooff et al., 2011; van Hooff & Blocken, 2013), as well as greenhouse and livestock buildings (Bartzanas et al., 2007; Bjerg et al., 2008; Osorio, 2010; Osorio et al., 2011; Bjerg et al., 2013).

However, in order for a CFD model to give useful information about air and pollutant motion within a NV livestock barn, it needs to be properly validated with experimental data such as air temperature (Osorio et al., 2011), air velocity (Wu et al., 2012) and average barn gaseous concentrations of ammonia ($NH_3$) (Rong et al., 2011) and carbon dioxide ($CO_2$) (Wu et al., 2012).

The $CO_2$ is an important gas in livestock buildings because a good percentage of its total measured concentration in barn airspace comes from animal metabolic activity and manure decomposition; $CO_2$ has also been considered as a preferred traces gas to monitor emissions of other pollutants in livestock barns due to its similarity to most of the target pollutant gases in these kinds of environment, such as proximity to the emitting sources of target gases and dispersion patterns (Pedersen et al., 2008). In addition, $CO_2$ production models for the main livestock categories have been presented by CIGR (2002), which can be implemented to CFD models. The CIGR $CO_2$ production model from livestock can accurately estimate $CO_2$ production in an hourly basis, and includes the effect of animal activity throughout the day. Nevertheless, a CFD model implemented with the CIGR $CO_2$ production model that is validated with an extensive grid of $CO_2$ concentration data collected along the livestock barn is so far inexistent in current literature. Such models once validated, may be used to estimate emissions and barn ventilation rates for a wide range of combined variables such as outside wind speed and direction, include the effect of animal activity on hourly basis emissions. Hence, this study was designed to assess the combined use of a CFD model and the CIGR $CO_2$ production model to predict and validate air flows and $CO_2$ distribution in a naturally ventilated dairy cow barn.

## Material and methods

This work was developed at the Department of Agricultural Engineering (DEA) of the Federal University of Viçosa (UFV), campus of Viçosa, State of Minas Gerais, Brazil and at the Livestock Research Institute at the Wageningen University and Research (WUR) Centre, Wageningen, the Netherlands. To solve the proposed problem, Computational Fluid Dynamics (CFD) was used to simulate the air motion and dispersion of heat and mass in a naturally ventilated dairy cow barn.

The results of a simulation of heat and $CO_2$ generation within the dairy cow barn at typical conditions during the summer time were compared to experimental values, with the objective of validating the data. This model can be used in the design of a monitoring system as well as in the characterization of new scenarios in order to unravel the aerial and gaseous dispersion processes occurring within the barn with the ultimate goal of understanding emission and ventilation rates from these kinds of barns. A

detailed description of the dairy cow barn, developed CFD model and validation strategy is presented below.

## Description of the experimental barn

The relatively new building is east-west oriented and has dimensions of 67 Lenght × 38 Width × 4 Side m (L × W × H), and a roof with 37% slope. The building envelope is composed of insulated roof and concrete side walls, the lateral openings on both sides are 2.75 m high, protected with stainless steel screens with openings of 0.05 × 0.05 cm and has manually operated curtains. In the eastern extremity of the building there is a deep litter area of 10L × 21W m. The central part of the building comprehends the cubicles area of 42L × 21W m, where 3 double-rows of cubicles (paper chips bedding), feeding alleys on both sides (north and south). The last section of the barn is at the most western side, and has an area of 13L x 21W m with similar cubicles and bedding system, where the heifers are kept.

Barn cubicles area had slatted walking alleys, an automatic scraping robot, and manure was stored in a deep pit space of 65L × 21W × 2D m located under the slats. Manure was removed twice a year, usually during early spring and fall seasons. The lactating cows had free access to 3 milking robot systems and the raw milk was stored in a thermally isolated container placed in a conjugated room at the east extremity of the barn. All cows were kept inside year long and were fed with concentrate, and either fresh grass, silage or any combination of the latter, depending on season.

## Development of barn geometry, mesh and mesh test

The internal airspace of the naturally ventilated barn was represented in the computational domain by drawing barn´s geometric shape with the software Rhynocerus®. The geometry of the barn consisted of two different domains. One domain (figure 1 - A) represented the region within the barn that was occupied by the cows, cubicles structures, internal walls, along with feeding and watering appliances, milking robots, and other equipment. The representation of groups of objects within the livestock barn by a porous media was suggested by Svidt et al. (1998) and Wu et al. (2012), to whom the internal objects are too complex to be included in the model, requiring overly refined meshes that would lead to an exponentially high number of time steps prior to reach convergence of the solution. The porous domain was divided into three other subdomains, one was occupied by dry and pregnant cows, other

occupied by the milking cows and another occupied by the heifers. The second domain (figure 1 - B) represented barn space occupied by fluid only, i.e. air and the gases generated by the cows and their manure. The geometry respective to the fluid domain had planes that were later designated as air inlet and outlets. Both geometries were, then, imported into the environment of the software ANSYS ICEM CFD® for mesh development.

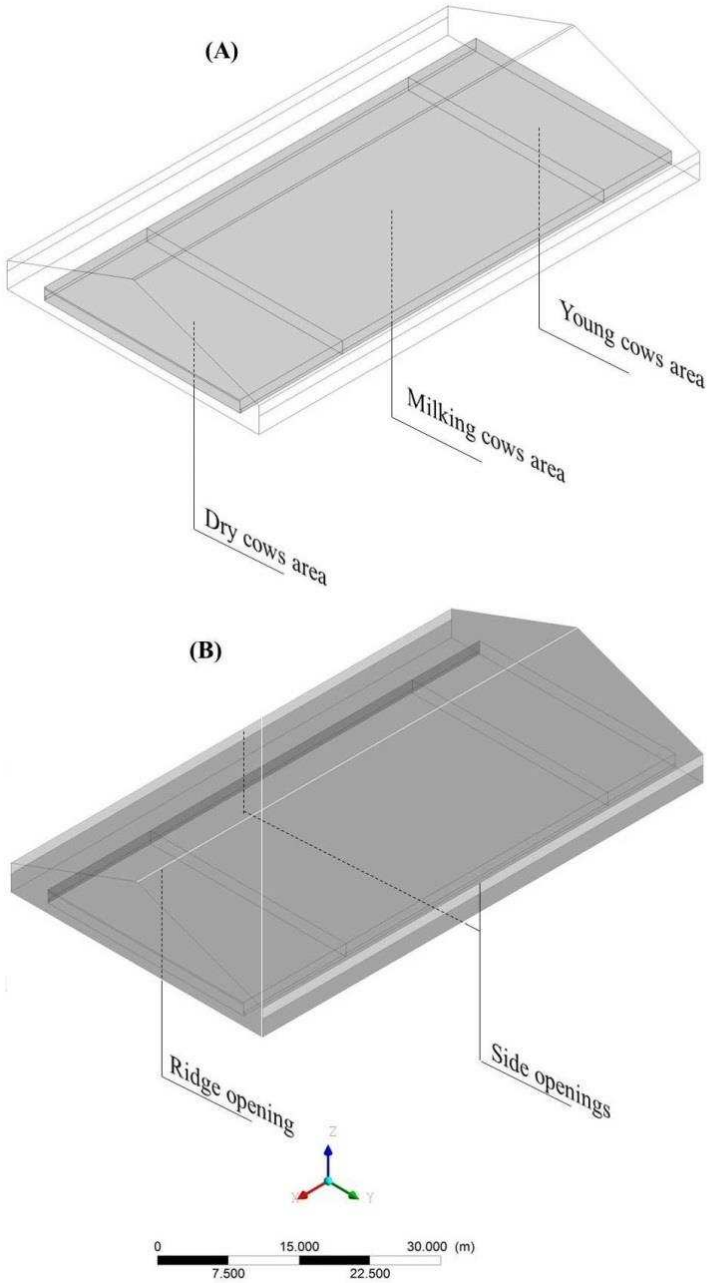


Figure 1. Geometry and design specifications of the experimental building.

During the mesh development step, an initial very refined mesh was created out of a mixture of hexahedral and tetrahedral elements (hexahedral-dominant mesh). A CFD model was implemented to this mesh, in which air entered through the inlet side at a speed of 4.0 m $s^{-1}$ (mean wind speed of the location where the barn is actually situated). This air flow through the building was considered as isothermal and steady state. The solver ANSYS CFX® was then used to find a solution of the air flow patterns for this model. Then the same model was run with a slightly coarser mesh, which also had the computational cost recorded. The use of a coarser mesh (smaller number of elements or cells) will lead to a smaller number of time steps to reach solution convergence. This procedure was repeated until the reducing computational cost of the coarser mesh was no different than the previous one. The last mesh was considered the ideal one for this study. The mesh characteristics are presented in table 1, and were graphically represented in figure 2.

Table 1. Mesh characteristics

| **Parameter** | **Free airspace** | **Milking cows AOZ*** | **Dry cows AOZ** | **Young cows AOZ** |
|---|---|---|---|---|
| Dimensions (m) | 67L×38W×4H | 40.0L×29.3W×1.7H | 15.3L×29.3W×1.7H | 10.0L×29.3W×1.7H |
| Volume ($m^3$) | 14845.1 | 1992.4 | 762.1 | 498.1 |
| Number of cells | 56671 | 11828 | 3578 | 3982 |
| Type of media | Fluid | Porous/fluid | Porous/fluid | Porous/fluid |
| Media porosity (%) | - | 91.8 ± 0.1 | 96.3± 0.2 | 92.5± 0.1 |

*Animal occupied zone.

The porosity of the AOZ meshes were estimated based on animal stocking density, animal count, animal body weight an estimated animal body volume (Arthur et al., 1997; Archer et al., 1998). An additional percentage of the space occupied by other solid material present in the Animal Occupied Zone (AOZ) was added to the total porosity.

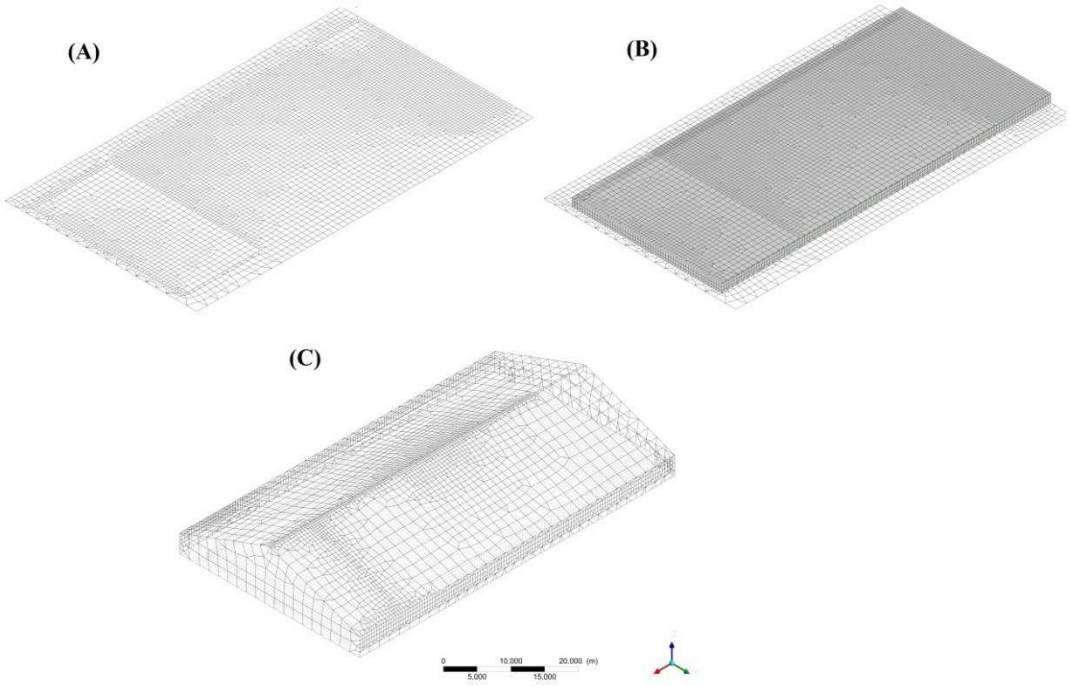


Figure 2. Mesh basis (A), porous domain (B) and fluid domain (C).

**Theoretical considerations of CFD modeling and boundary conditions**

The analysis of moment, mass and heat transfer in every element presented in the developed mesh for non-isothermal fluid flow is represented as the system of differential equations presented below (Rocha et al., 2013).

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \left(\rho \vec{v}\right) = S_m \tag{1}$$

$$\frac{\partial \left(\rho \vec{v}\right)}{\partial t} + \nabla \cdot \left(\rho \vec{v}\vec{v}\right) = -\nabla P + \left(\bar{\bar{\tau}}\right) + \rho \vec{g} + \vec{F} \tag{2}$$

$$\frac{\partial \left(\rho E\right)}{\partial t} + \nabla \cdot \left(\vec{v}\left(\rho E + P\right)\right) = \nabla \cdot \left( \kappa_{ef} \nabla T - \sum_j h_j \vec{J}_j + \left(\bar{\bar{\tau}} \cdot \vec{v}\right)\right) + S_h \tag{3}$$

where:

$\rho$ - Specific mass $\left(kg \cdot m^{-3}\right)$

$t$ - Time $\left(s\right)$;

$\vec{v}$ - Velocity flux vector $\left(m \cdot s^{-2}\right)$

$S_m$ - Mass added to the continuous phase $\left(kg \cdot m^{-3} \cdot s^{-1}\right)$

$P$ - Static pressure $\left(Pa\right)$;

$\bar{\bar{\tau}}$ - Stress tensor $\left(N \cdot m^{-2}\right)$

$\rho\vec{g}$ - Gravitational force by unit of volume $\left(N \cdot m^{-3}\right)$

$\vec{F}$ - External forces per unit of volume $\left(N \cdot m^{-3}\right)$

$E$ - Specific energy $\left(J \cdot kg^{-1}\right)$

$\kappa_{ef}$ - Effective thermal conductivity $\left(W \cdot m^{-1} \cdot K^{-1}\right)$

$T$ - Temperature $\left(K\right)$;

$h_j$ - Coeficient of mass transfer $\left(m \cdot s^{-1}\right)$;

$\vec{J}_j$ - Difusive flux of the species j, $\left(kg \cdot m^{-3} \cdot s^{-1}\right)$

$S_h$ - Mass added or removed through the continuous phase $\left(kg \cdot m^{-3} \cdot s^{-1}\right)$

Equation 1 represents the conservation of mass within each mesh cell. Equation 1 represents the Second Newton´s Law of Moment Conservation, also called Navier Stokes´ Equation (Tu et al., 2007), and is used to describe the movement of air across the porous and fluid media within the barn. Equation 3 describes the dispersion in the air of the heat generated by the animals.

The Reynolds tensor was modulated with the use of the standard K-ε turbulence model, which evaluates fluid viscosity ($\mu_\tau$) from the relationship between turbulent kinetic energy ($k$) and velocity fluctuation dissipation rate ($\varepsilon$) (Rocha et al., 2013).

The equations for total heat production rate under thermoneutrality ($\Phi_{tot}$) for the dairy cows, calves and heifers were calculated with the equations presented below based on (CIGR, 2002).

For dairy cows:

$$\Phi_{tot,dairy} = 5.6m^{0.75} + 22Y_l + 1.6\times10^{-5}\, p^3 \quad (4)$$

For calves:

$$\Phi_{tot,calves} = 6.44^{0.7} + \left[\frac{13.3Y_2\left(6.28 + 0.0188m\right)}{1 - 0.3Y_2}\right] \quad (5)$$

For heifers:

$$\Phi_{tot,heifers} = 7.64^{0.69} + Y_2\left[\frac{23}{M} - 1\right]\left[\frac{57.27 + 0.302m}{1 - 0.171Y_2}\right] + 1.6\times10^{-5}\, p^3 \quad (6)$$

where:

$\Phi_{tot,\ dairy}$, $\Phi_{tot,\ calves}$, $\Phi_{tot,\ heifers}$ - Total heat dissipation from dairy cows, calves and heifers, respectively (W);

m - Body mass of the animal (kg);

$Y_1$ - Milk production (kg $day^{-1}$);

$Y_2$ - Daily body weight gain (0.5 kg $day^{-1}$)

p - Number of days of pregnancy (d);

M - Energy content of feed, MJ $kg_{dry\ matter}^{-1}$.

Since the equations of $\Phi_{tot}$ refer to thermoneutral conditions (20°C) for, at lower temperatures, the total heat production increases and at higher temperatures it decreases. Hence, for temperatures different than the termoneutral conditions, heat dissipation values were added to a correction factor that was calculated from equation 7.

$$\Phi_{corr,T} = 4 \times 10^{-5} \left(20 - T\right)^3 \quad (7)$$

where:

$\Phi_{corr,T}$ - Correction factor for temperature on total heat product on from the animals, based on the thermoneutral level of 20 °C, non-dimensional;

T - Indoor air temperature (°C).

The $CO_2$ production by the animals at house level, i.e. considering $CO_2$ produced by both the animals and stored manure, was estimated with the sinusoidal equation presented by Pedersen et al. (2008), as equation 8.

$$PR_{CO_2} = c \cdot \left[1 - a \cdot \sin\left(\frac{2\pi}{24}\right) \cdot \left(h + 6 - h_{min}\right)\right] \quad (8)$$

where:

c - $CO_2$ production, 0.170 $m^3\ h^{-1}\ hpu^{-1}$ for calves and 0.200 $m^3\ h^{-1}\ hpu^{-1}$ for dairy and dry and pregnant cows (Pedersen et al., 2008).

a - Constant expressing the amplitude with respect to the average activity of the day, 0.23 for dairy, pregnant and dry cows, 0.38 for heifers (CIGR, 2002);

h - Time of the day (h)

$h_{min}$ - Time of the day with minimum activity (hours after midnight).

The information on cow count, body weight and milk production needed to estimate total heat and $CO_2$ production are presented in table 3. Constant values for outside air temperature, wind speed and background $CO_2$ concentration were implemented to the CFD model as also described in table 3. The meshes respective to porous and fluid media were coupled with the interface tool of the pre-processing software. Barn inlet and outlets were specified to the surfaces of the mesh, as indicated by the white and yellow arrows in figure 3.

Table 3. Characteristics of the housed dairy cows and model constant values

| | |
|---|---|
| Number of milking cows | 136 |
| Number of dry cows | 24 |
| Number of pregnant young cows | 33 |
| Milking cows live weight (kg) | 663 |
| Dry cows live weight (kg) | 663 |
| Pregnant young cows live weight (kg) | 500 |
| Milk production (kg/cow/day) | 30.6 |
| Avg. outside air temperature ($^{o}$C) | 22 ± 1 |
| Mean wind speed at inlet (m $s^{-1}$) | 4.0 ± 0.6 |
| Mean wind direction at inlet | SE |
| Mean background carbon dioxide concentration (ppm) | 404 ± 6 |
| Relative pressure at outlets (Pa) | 0 |

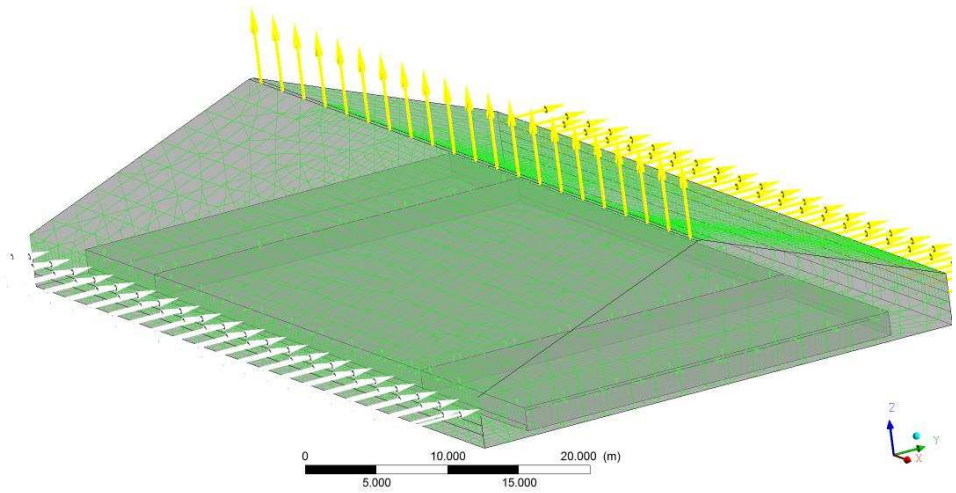


Figure 3. Inlet and outlet positions

The calculated constant heat and $CO_2$ produced by each porous media are presented in table 4. The used convective heat transfer and Nusselt number (Nu) were calculated according to the fluid properties and dimensions of air inlet to the barn, and are also presented in table 4. The velocities of release of $CO_2$, turbulence kinetic energy and eddy dissipation were based on those presented by Fiedler et al. (2013), Bartzanas et al. (2007) and Heber et al. (1996), measured at similar conditions to those of this study.

Table 4. Parameters implemented into the porous media

| Parameter | Milking cows | Dry cows | Young cows |
|---|---|---|---|
| Total heat production(corrected for temp., hpu) | 200 ± 2 | 19±1 | 25±1 |
| Convective heat transfer of the air (h, W $m^{-3}$ $K^{-1}$) | 26 ± 1 | 26 ± 1 | 26 ± 1 |
| Average air temperature ($^oC$) | 24 | 24 | 24 |
| Nusselt number (Nu) at 24 $^oC$ | 64225 ± 2159 | 64225 ± 2159 | 64225 ± 2159 |
| $CO_2$ release velocity at source (U, m $s^{-1}$) | 0.15 | 0.15 | 0.15 |
| $CO_2$ release velocity at source (V, m $s^{-1}$) | 0.31 | 0.31 | 0.31 |
| $CO_2$ release velocity at source (W, m $s^{-1}$) | 0.01 | 0.01 | 0.01 |
| Turbulence kinetic energy ($m^2$ $s^{-2}$) | 0.1 | 0.1 | 0.1 |
| Turbulence eddy dissipation ($m^2$ $s^{-3}$) | 0.099 | 0.099 | 0.099 |

After the pre-processing step, the software ANSYS CFX® was used to implement the proposed model, with the following assumptions: (a) transport in steady state and (b) incompressible flow. A Residual Mean Square (RMS) error of less than $10^{-4}$ was adopted as convergence criteria.

## Validation procedure

In order to validate the developed CFD model, $CO_2$ concentrations were actually measured inside the dairy cow barn with three lines of sensors. Each line had a total of 5 Non-Dispersive Infra-Red (NDIR, model SD-GAS-025, Sensor Data B. V., Rijswijk, the Netherlands) sensors calibrated in the laboratory. Each line was placed on top of North, Middle and South cubicle alleys (figure 4). The NDIR sensor consists of a portable sensor housed in a 0.20L × 0.05W × 0.05H m polyethylene enclosure, with vents though which ambient air enters either by local convection or passive diffusion. Sensor measuring range is 0.2 - 5000 $ppm_v$ of $CO_2$ concentration, sensitivity of 20 ppmv ± 1% of the reading and accuracy of 30 ppmv ± 2%. The NDIR sensors were excited with a voltage of 1200 mV, and connected to a datalogger system (CR1000, Campbell Scientific, Inc., Logan, Utah) located in the shelter placed outside the barn (figure 4). $CO_2$ concentrations were measured every 2s, and 5 min averages were stored

by the datalogger. Experimental data was collected for a total of 120 min, during this period screen height of the barn were kept at 50% open on each side.

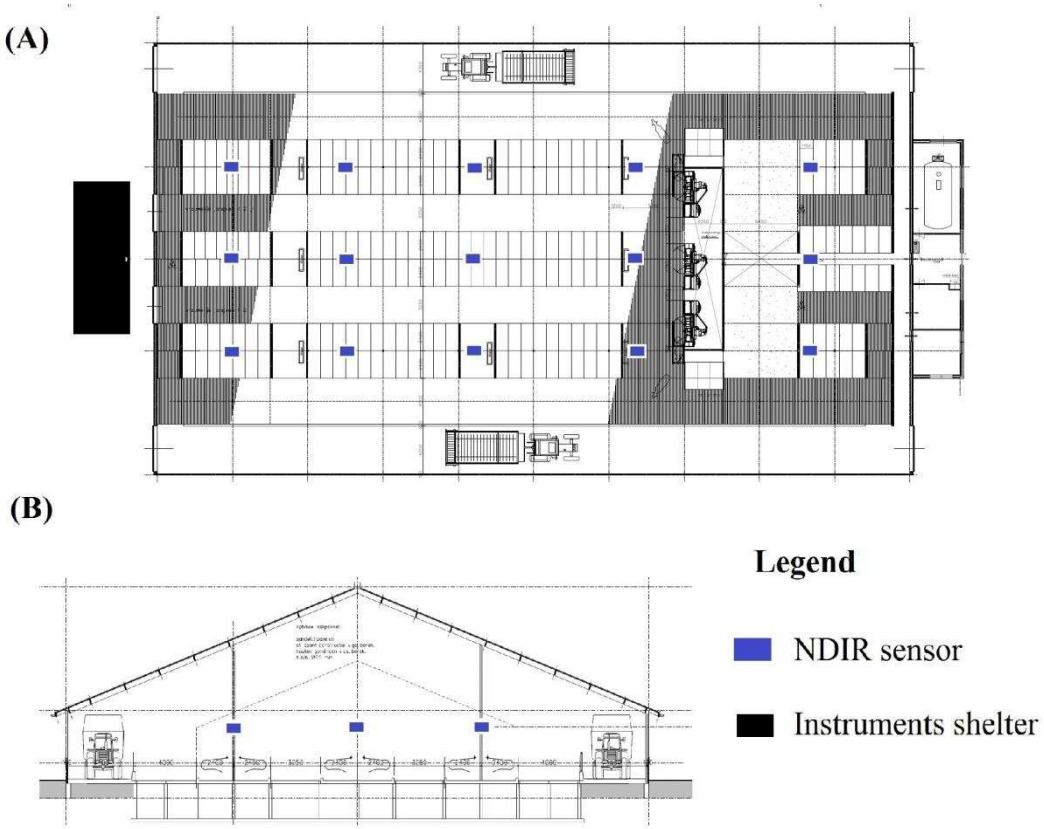


Figure 4.Top (A) and transversal (B) view cuts of the investigated barn with the allocation of the NDIR sensors for sampling of carbon dioxide ($CO_2$, not to scale).

The results obtained by the CFD model were verified and compared with the corresponding data obtained experimentally with the NDIR sensors. The concordance between the measured values and those described by the CFD model were evaluated by calculating the Normalized Mean Squared Error (NMSE). A sample of 15 experimental measurements of all data was used.

$$NMSE = \frac{\left( \frac{\sum_{n} \left( [CO_2]_{CFD,i} - [CO_2]_{NDIR,i} \right)^2}{n} \right)}{\left( \overline{[CO_2]}_{CFD} \cdot \overline{[CO_2]}_{NDIR} \right)} \quad (13)$$

where:

| | | |
|---|---|---|
| NMSE | - | Normalized Mean Squared Error (non-dimensional); |
| $[CO_2]_{CFD,i}$ | - | $CO_2$ concentration predicted by the CFD model ($ppm_v$); |
| $[CO_2]_{NDIR,i}$ | - | $CO_2$ concentration measured experimentally with the NDIR sensors ($ppm_v$); |
| n | - | Number of observations; |
| $\overline{[CO_2]}_{CFD}$ | - | Average $CO_2$ concentration predicted by the CFD model ($ppm_v$); |
| $\overline{[CO_2]}_{NDIR}$ | - | Average $CO_2$ concentration measured experimentally with the NDIR sensors ($ppm_v$); |

## Results and discussion

### Convergence of model solution

The charts of the solution convergence of the proposed CFD model are presented in figure 5. The plots in figure 5 indicate that all parameters converged after 120 time steps, which is relatively small, given the complexity of the model. This indicates that further refinements may be implemented to model mesh, or the generation of other pollutant gases such as $NH_3$ may be added to it, without extreme increase in convergence time steps number. The implementation of $NH_3$ generation to the model will be in the next steps of its development.

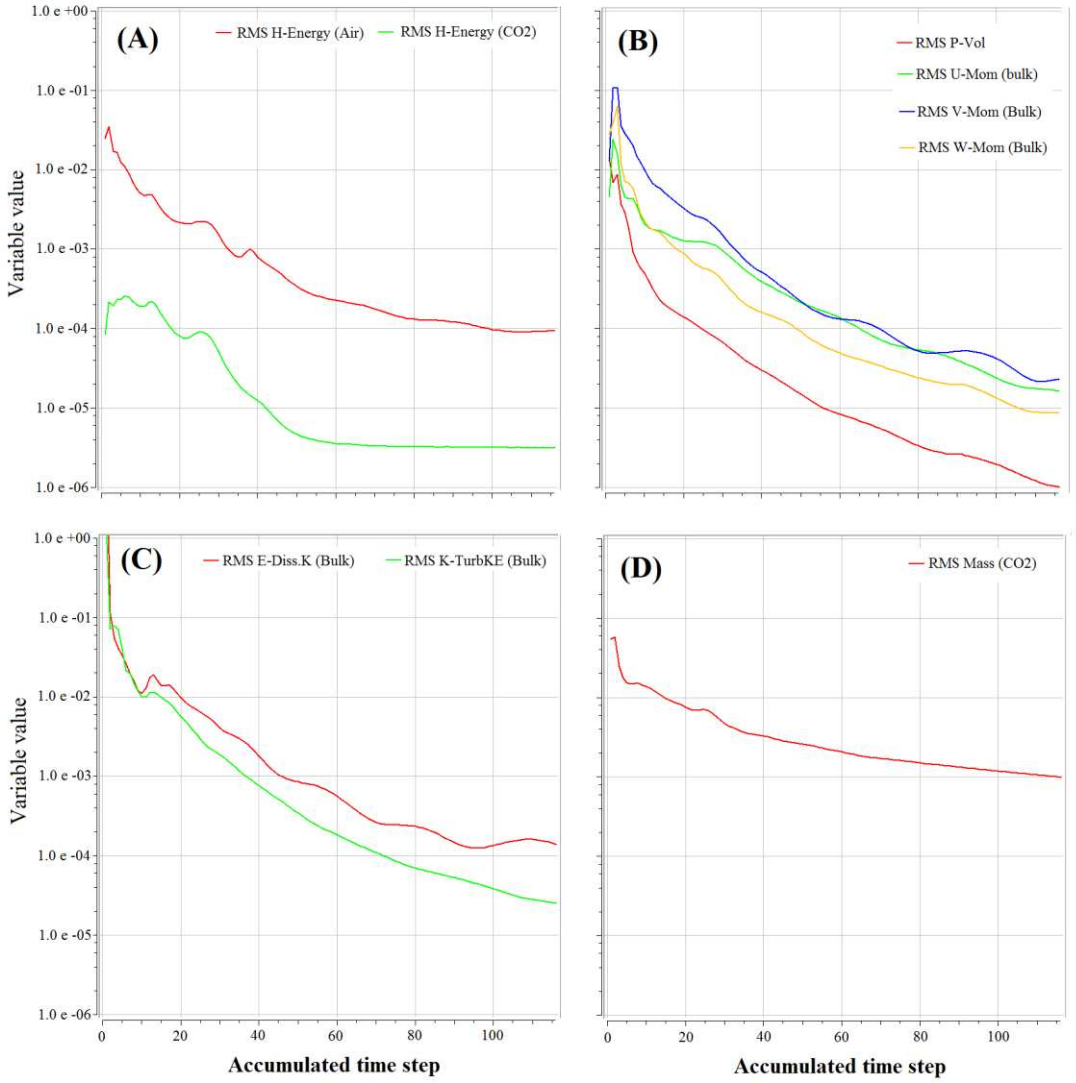


Figure 5. Convergence of model solution as a function of accumulated time step. Solution convergence for (A) the energy balance for air and $CO_2$, (B) for the moment transfer equation, (C) for the turbulence dissipation equation and (D) for the mass balance of $CO_2$ volume fraction.

## Analysis of air flow patterns with the NV barn

The solution of the proposed CFD model was then open with the post-processing ANSYS CFX POST® for visual analysis of the air flow patterns and $CO_2$ concentration data. In figure 6-A one can see the velocity vector field in a vertical cross-section of the dairy cow barn. A relatively smaller density of velocity vectors within the AOZ indicates that mean air speed was lower at his region. The lower air velocity is a result of the flow resistance imposed by the porous media, and has a direct effect on the

mixing of air with the gases produced by animals and manure, as previously discussed in Chapter 3.

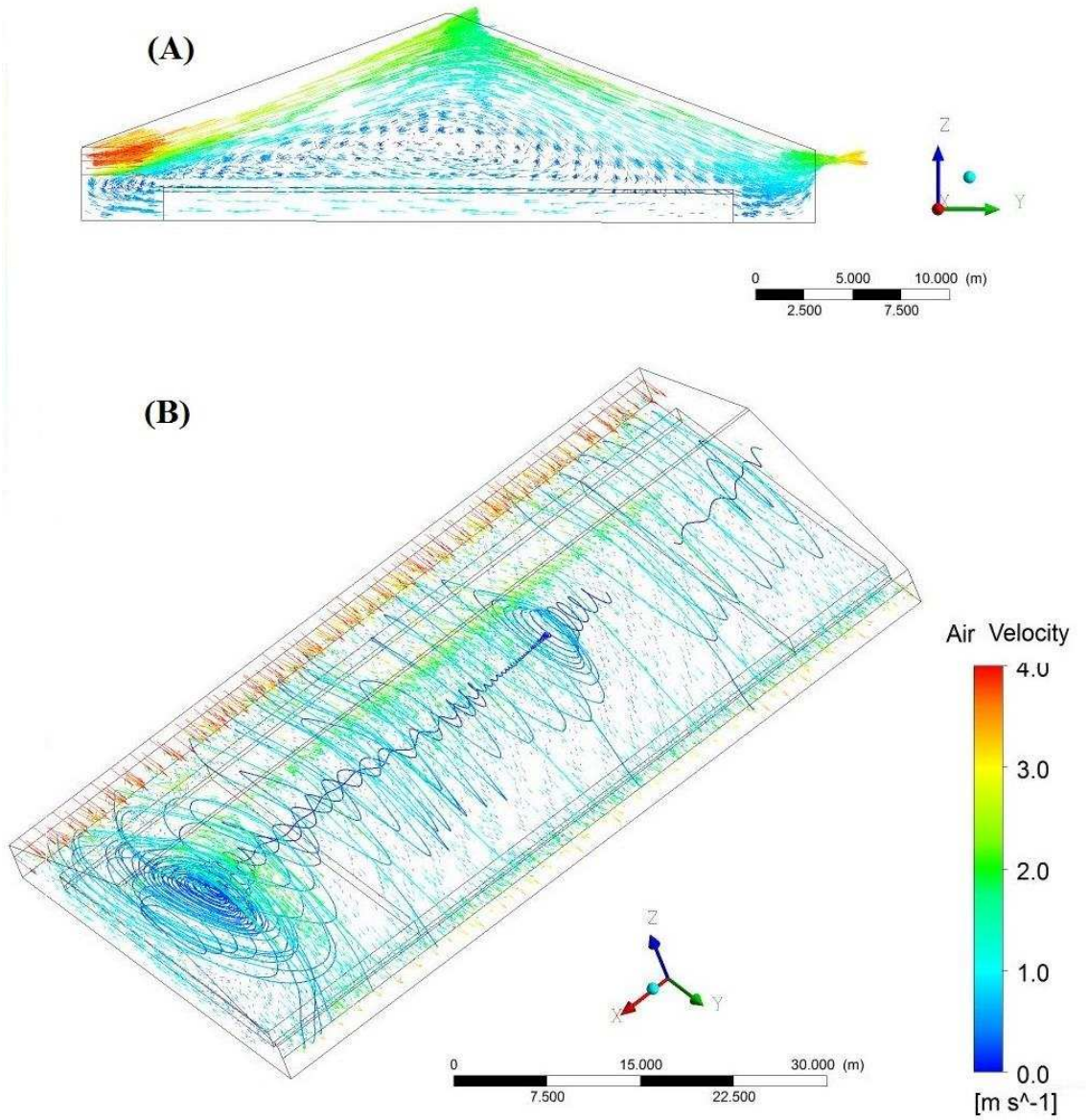


Figure 6. Air velocity vector field on a cross section of the barn (A), and 3D view of air flow streamlines (B) within the naturally ventilated dairy cow barn.

The streamlines shown in figure 6-B indicate the formation of a vortex on top of the AOZ in the central region of the ventilated airspace. According to the figure 6-B, the vortex crosses the entire length of the barn. The vortex is an important feature that allows for mixing of the gases produced in the AOZ with air, and that region has presumably more homogeneous mixing of gases. It is important to notice, however, that

this air flow configuration is only valid for winds that incident on the inlet opening. Winds at other angles will presumably yield in other motion configurations within the barn. Hence, modeling the effect of winds with different incident angles may be a topic for further research in the field.

## Validation of the CFD model

The $CO_2$ concentration distribution profile predicted by the CFD model at a horizontal plane 3 m above the slats is presented in figure 7-A. From the figure 7-A, one can see that at 3 m of height, $CO_2$ concentrations reached higher levels in the region occupied by the milking cows. This is due to the higher stocking density in that zone (8.5 $m^2 cow^{-1}$) as compared to that in the zones occupied by the dry and young cows (18.7 $m^2$ $cow^{-1}$ and 12.0 $m^2$ $cow^{-1}$, respectively), and to the fact that milking cows have higher metabolic rates and thus produce more $CO_2$ than the other cows´ categories.

The concentrations of $CO_2$ measured by the NDIR sensors in 15 points across the barn were averaged out over a period of 120 min, and concentrations for the points in between two sensors were obtained by interpolation. The results are presented in figure 7-B. A comparison of the concentration profiles in figure 7-A and figure 7-B allows one to see the similarities between the values predicted by the CFD model and those obtained experimentally. Slight discrepancies between the concentration profiles might have arisen from the fact that for the experimentally obtained data, the wind direction may have fluctuated over the period of 120 min, while it was kept constant by the CFD model. The $CO_2$ concentration predicted from the CFD model at the same points where the NDIR sensors were located were extracted from the model solution, and plotted against the equivalent average concentrations measured experimentally with the NDIR sensors. The resulting plot is shown in figure 8.

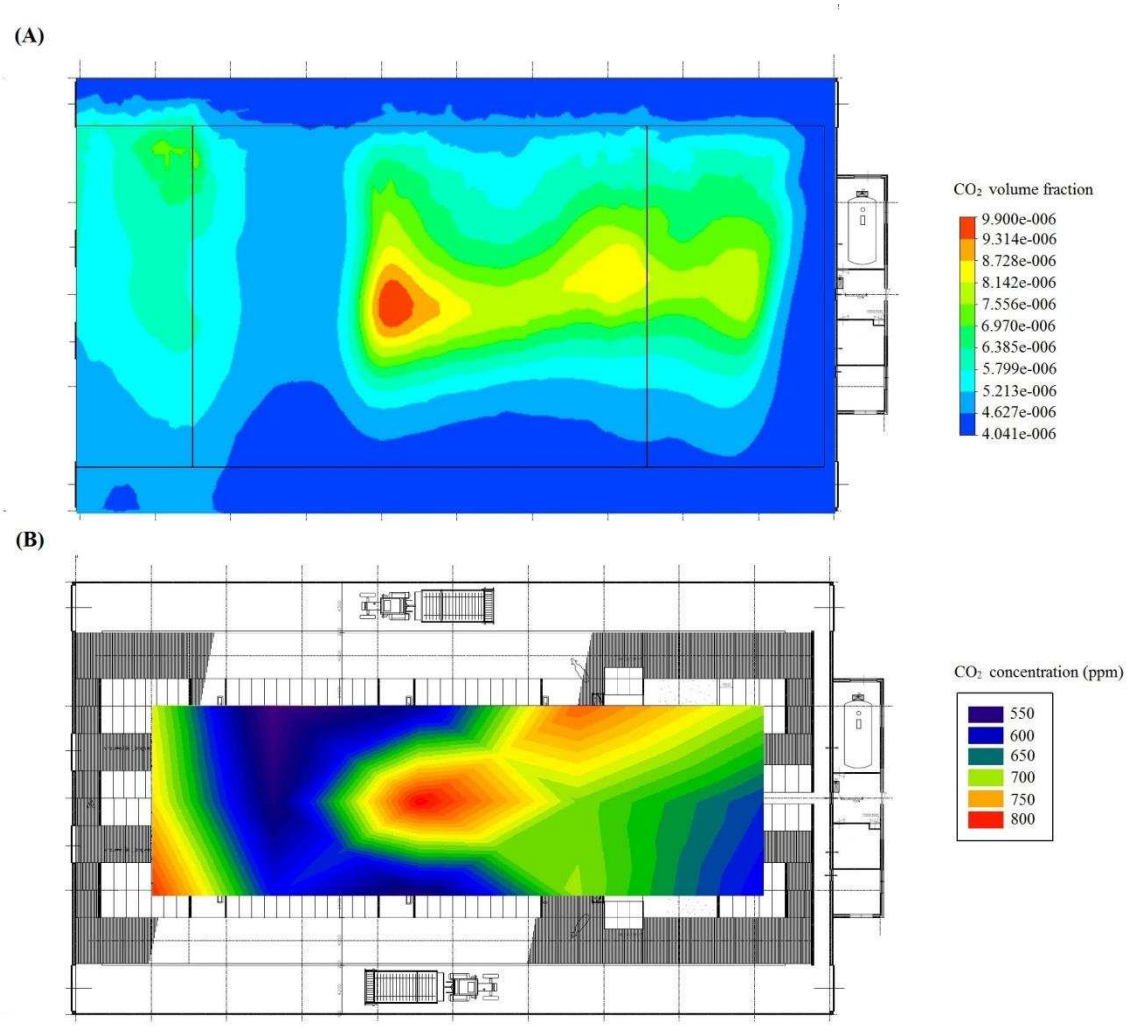


Figure 7. Comparison of $CO_2$ distribution profile on a horizontal plane at 3 m from the slats, (A) Predicted by the CFD model and (B) measured experimentally with NDIR sensors.

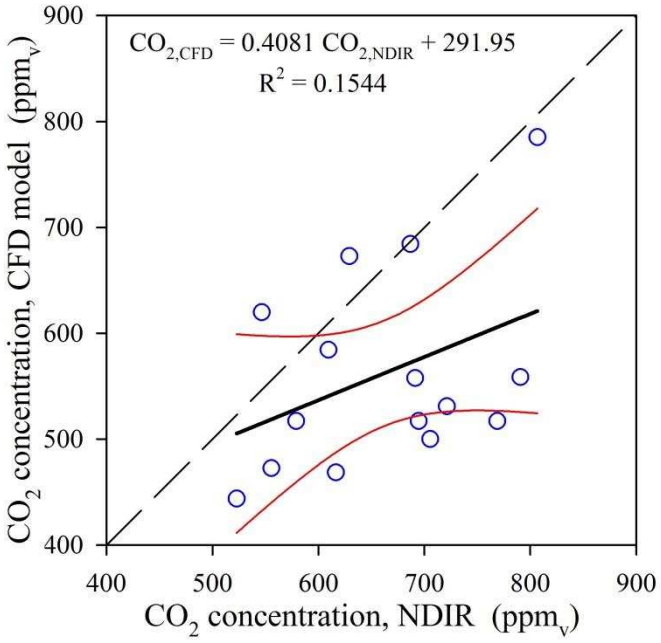


Figure 8. Regression between $CO_2$ concentrations predicted by the CFD model and those obtained experimentally with the NDIR sensors. The dashed line represents a 45° slope line and the red lines represent a 95% confidence band.

The plot in figure 8 indicates that the concentrations predicted by the CFD model presented some positive linear correlation to the experimental data ($R^2$ = 0.15). Fluctuations between predicted and measured concentrations might be due to the variability in wind direction and intensity, as indicated previously. The calculated NMSE for the studied case was 0.053. The tolerance NMSE value normally used for the kind of model presented in this study is 0.250, which indicates that the CFD model is capable of predicting air movement and $CO_2$ distribution profile within the considered barn.

**Further discussions**

At the moment that this paper was written, the CFD model is still in development, although the first results presented above already indicate that it might be feasible to predict air motion patterns in the dairy cow barn. The next steps of model development will be to test the effect several wind directions and intensities on the predictability of $CO_2$ concentrations and other parameters. After this step, we will have a larger database to perform validation and expect that the NMSE will decrease even further.

Another step to be taken with future progress of this research is to play with size of inlet opening and its effect on air flow patterns and change in $CO_2$ dispersion profiles. The purpose of this step is to answer the question of how much further the opening size can increase, so that the CIGR $CO_2$ generation equations can be used without including large errors to the ventilation and emission rates estimates. There is a concern that if the opening size becomes too large, the $CO_2$ can no longer be used as a tracer.

The ultimate goal of this project is to implement the actual CIGR $CO_2$ production models into the model, and let them calculate the $CO_2$ production in an hourly basis, based on time of the day, wind speed and direction, and other conditions such as outside air temperature. This will be done by implementing subroutines in the FORTRAN 90 programming language to customize the particularities of the combinations between barn outside and inside conditions carried out by ANSYS CFX® during processing and interpreted by the CFX Expression Language (CEL).

## Conclusions

A computer model was developed with the Computational Fluid Dynamics (CFD) technique and was used to simulate the air motion, heat and $CO_2$ generation and dispersion in a NV dairy cow barn. The results of a simulation performed with the model for typical conditions during the summer time in Northern Europe were compared to experimental data, with the objective of validating the data. The developed CFD model showed to be suitable for the prediction of air flow patterns and $CO_2$ concentration profiles within the studied NV dairy cow barn, and presented an estimated Normalized Mean Square Error of 0.053. It is expected that further improvement of the model will be suitable for calculation of air flow and emission rates on an hourly basis, and as a function of outside conditions such as temperature, wind speed and direction.

## Acknowledgments

The authors would like to thank the Dutch Ministry of Economic Affairs and the Dutch Dairy Board within the Program “Duurzame Zuivelketen” (Sustainable Dairy Chain). The authors would also like to acknowledge the Brazilian government funding agencies: CNPq (Portuguese acronym for National Council for Scientific Research and

Development) and CAPES (Portuguese acronym for Council for Improvement of Highly Educated Personnel) for supporting researchers.

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# CHAPTER 5. A REFINED PROTOCOL FOR CALCULATING AIR FLOW RATE OF NATURALLY-VENTILATED BROILER BARNS BASED ON $CO_2$ MASS BALANCE

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A manuscript submitted to the Journal DYNA-Medellín

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## Abstract

Accurate determination of ventilation rate (VR) in confined animal houses is necessary to reduce errors in estimation of aerial emissions from the litter/barn. This study was conducted to evaluate four relatively simple protocols for use in naturally ventilated (NV) barns. The test protocols were first evaluated with a mechanically ventilated (MV) broiler barn by comparing its VR obtained from $CO_2$ mass balance with the VR measured using fan traverse (i.e., the reference value), and the best ones were used to calculate VR in the NV barn, where the reference method could not be applied. Concentrations of $CO_2$ were measured according to two different sampling schemes:

(S1) average of indoor measurements along the length of the building at two heights of 0.5 m and 1.5 m from litter floor, and outdoor measurements along the side of the building; and (S2) average of indoor measurements along the length of the building at a single height of 0.5 m from litter floor, and outdoor measurements along the side of the building. Dynamic metabolic $CO_2$ production rate of the birds was predicted with two different algorithms: (A1) remaining constant throughout the dark and light periods, and (A2) varying with animal activity in an hourly basis. The four evaluated test methods consisted of combinations of different sampling schemes and algorithms. The results demonstrated that incorporation of diurnal animal activity in calculation of metabolic $CO_2$ production combined with sampling $CO_2$ concentration yielded the best estimates of building VR, ranging from (0.8 ± 0.2) $m^3\ h^{-1}\ bird^{-1}$ and (8.9 ± 0.8) $m^3\ h^{-1}\ bird^{-1}$ at the ages of 1 and 6 week, respectively, while there was no significant impact of the tested sampling schemes in the estimates of VR for the MV barn, as compared to the reference method. We also concluded that for further refinement of the protocol, an update of the metabolic $CO_2$ production from modern broiler strains under different environmental temperature is needed. The evaluated protocol represents a simple and effective mean to determine air flow rate in NV broiler barns that does not require the use of sophisticated instruments or intensive data acquisition.

**Keywords:** Building ventilation rate, aerial emissions from broiler barns, $CO_2$ mass balance, Bland-Altman chart.

## Introduction

A considerable amount of published literature on ammonia ($NH_3$) emissions from poultry production is devoted to the quantification of $NH_3$ emissions from mechanically ventilated (MV), environmentally-controlled poultry houses (Xin et al., 2011). This kind of installation, however, is not typical in Brazil where poultry production systems feature open sidewalls without total control of the inside conditions. This practice is to take advantage of the tropical climates for natural ventilation (NV) and to reduce production costs (Tinôco, 2002). However, there are technical challenges associated with measuring building ventilation rate (VR) and thus aerial emissions of such facilities (Ogink et al., 2012).

Determination of VR in MV buildings is relatively easier as compared to NV buildings, because VR in MV barns can be determined by directly measuring the airflow rates through all openings or ventilation fans of the building and then totalized to obtain the overall building VR (Calvet et al., 2012). On the other hand, NV barns have large open contact areas with its outdoor environment, which is difficult to define. There exist various approaches to determining VR of NV barns. One of the methods is based on use of tracer gas, applicable to both MV and NV buildings. The technique is based on mass balance of a tracer gas with known release rate inside the building. Several gases can serve as tracers, with naturally produced carbon dioxide ($CO_2$) being the most used because of advantages such as homogeneity in the air and reduced costs since it is readily available from the housed animals (Xin, et al., 2009).

The challenge in using $CO_2$ as a tracer to determine VR is the proper estimation of metabolic $CO_2$ production by the animals and other sources such as manure. There are two major methods of determining metabolic $CO_2$ production: one requires information of the respiratory quotient (RQ), and simplifies animal activity in dark and light periods (Xin et al., 2009); (b) the other approach includes hourly variation of animal activities on the total metabolic $CO_2$ produced (Pedersen et al., 2008; Calvet et al., 2011). The question of how these two approaches compare to one another still needs to be answered. On the other hand, Zhang et al. (2011) mentioned that a crucial challenge for the determination of VR in NV barn is choosing the locations for measuring the concentrations of $CO_2$. This reinforces the importance of the development of sampling schemes that lead to monitoring representative average barn $CO_2$ concentrations.

Hence, the objective of this study was to define and evaluate an effective protocol for determining VR of a NV barn from several alternative methods. The potential refinements (i.e., test methods) that were investigated included: (a) use of an algorithm that best represents the production and release of metabolic $CO_2$ in the barn, which includes either diurnal or constant animal activity effect, and (b) determination of a sampling scheme of $CO_2$ concentration that leads to the best average indoors concentration, amongst the tested schemes. Due to the non-existence of a reference method for determination of VR in NV barns that can be used to challenge the test methods, we applied these test methods to a MB barn, where the comparison with a reference method (summation of airflow from all exhaust fans) was possible, and the

test method that yielded the best fit to the reference value was then used for determination of VR in a NV barn.

## Material and methods

### Characteristics of the broiler barns and flock management

The study was conducted in two commercial broiler barns, one naturally ventilated (NV) and the other mechanically ventilated (MV), both located on the same farm in the state of Minas Gerais, Brazil. The MV barn had a dimension of 120.0 Lenght × 14.0 Width × 2.5 Side m (L × W × H), fiber-cement tile roof, and a polyurethane drop ceiling (the same material as used for the sidewall curtains). The sidewall curtains were closed most of the time, and the ventilation was provided with 8 newly installed exhaust fans (specified capacity of 39,329 $m^3$ $h^{-1}$ each at 1.5 HP and static pressure of 12.0 Pa) placed on the west end of the building. Fresh air was brought into the barn through air inlets located at the east end, and the inlet openings were adjusted manually, as needed. The ventilation program was based on indoor air temperature and consisted of 7 stages including minimum ventilation at the early age of the birds (< 3wk). The barn had an initial placement of 23,100 male Cobbs® chicks, and freshly dried coffee husks, serving as floor bedding, which was never used to raise broilers before. Chicks were reared up to marketing age of 45 d.

The NV barn that was used for the application of the best VR protocol had the dimension of 75 L x 12 W x 2.75 H m. It had ceramic tiles and polyurethane drop ceiling (same as used for sidewall curtains). Ventilation was provided through manual operation/opening of the sidewall curtains (fully open, half open, or nearly closed). The initial bird placement was 10,000 female Cobbs®, and had the same kind of non-used litter described for the MV barn. This flock was also reared up to a marketing age of 45 d.

The lighting program was similar for both flocks and followed the management guidelines of Cobb-Vantress (2009), consisting of 1-hour dark between the ages 2 - 10 d; then the number of dark hours was increased to 9, and then decreased again to 8, 7 and 6 hours of dark at the ages of 22, 23 and 24 days, respectively. The light schedule then remained the same until bird age was 39 d, when the number of dark hours was set to 5, decreasing one hour a night till pick up day. Because the birds were being reared during summer period in Brazil, dark hours were synchronized to sunrise, and thus the

time of minimum animal activity ($h_{min}$) in equation 4 usually occurred between 2:00AM and 5:00 AM.

**Sampling scheme and data collection**

Carbon dioxide concentrations were measured with a hand-held sensor (model AZ 77535 $CO_2$/Temp/RH Meter, AZ Instrument Corp., Taichung City, Taiwan) that had a measuring range of 0 ~ 9999 ppm, resolution of 1 ppm and accuracy of ± 30 ppm ± 5% of the reading (according to specifications, and calibrated at the factory). Data collection was done once every three hours, for a 48-hour period, performed weekly throughout the 7–week grow-out period. Monitoring of gaseous concentrations in different points within the barn was not done simultaneously, but collected within 15 min (as quick as possible) for each barn.

Sampling scheme 1 (S1): Indoors $CO_2$ concentrations were measured at three different distances along the central axis of the building (at 20, 60 and 100 m from the exhaust fans), and at two different heights (0.50 and 1.25 m above the litter). Outdoors $CO_2$ concentration was measured at three different points along the south side of the building, which was considered the air inlet, as during the experimental period the wind was consistently coming from the south.

Sampling scheme 2 (S2): Same as S1, except that the indoors concentrations were taken only at 0.5 m above the litter, e.g. closer to the $CO_2$ plume generated by the birds.

2.3 Algorithms for calculation of building ventilation rate (VR)

Building ventilation rate can be estimated through equation 1 (CIGR, 2002).

$$VR = \frac{A \times (CO_2)_{metabolic} + (CO_2)_{litter}}{\Delta[CO_2]} \quad (1)$$

where:

| | | |
|---|---|---|
| VR | - | the building ventilation flow ($m^3\ h^{-1}\ hpu^{-1}$); |
| A | - | the relative animal activity (non-dimensional); |
| $(CO_2)_{metabolic}$ | - | metabolic $CO_2$ production by the animals ($m^3\ h^{-1}\ hpu^{-1}$); |
| $(CO_2)_{litter}$ | - | the $CO_2$ released by the litter ($m^3\ h^{-1}\ hpu^{-1}$); |

$\Delta[CO_2]$ - $[CO_2]_{indoors}$ - $[CO_2]_{outdoors}$, the indoor and outdoor $CO_2$ concentrations, respectively (ppm).

CIGR (2002) define 1 hpu (heat production unit) as 1000 W of total heat at 20°C. Two different algorithms were tested to estimate building VR, as follows.

Varying metabolic $CO_2$ production (algorithm A1): For this algorithm, A in equation 1 was set constant and equal to 1, while the metabolic production of $CO_2$ was calculated using the same equations 2 and 3 that were used by Xin et al. (2009). Here, animal activity was simplified to a dark and light period behavior, represented by two different respiratory quotients (RQ).

$$[CO_2]_{metabolic} = \frac{THP}{\frac{16.8}{RQ} + 5.02} \quad (2)$$

$$THP = 10.62N \times m^{0.75} \quad (3)$$

where:

THP - total animal heat dissipation under thermoneutral conditions (W);

RQ - respiratory quotient, non-dimensional;

N - number of animals in the barn;

m - animal body mass (kg).

The RQ value for broilers used in this algorithm was 0.9 (Xin et al., 2009), for all ages. According to Xin et al. (2009), RQ values of tom turkeys remained constant and around 1.0 for days 1 – 35 of age, and since broilers and young turkeys are similar in their bioenergetics (Xin et al., 2009), we used a constant RQ value for the tested bird age range. In this algorithm, dark vs. night activity was taken into consideration by reducing THP during the night period by 25%, as recommended by Xin et al., (2009).

Varying relative animal activity (algorithm A2): For this algorithm, metabolic $CO_2$ production was set constant and equal to 0.180 $m^3\ h^{-1}\ hpu^{-1}$ for chicks with body weight < 0.5 kg and equal to 0.185 $m^3\ h^{-1}\ hpu^{-1}$ for body weight ≤ 0.5 kg (CIGR, 2002), while the relative animal activity was calculated with the equations used by Pedersen et al.

(2008), namely the animal activity is represented by a sinusoidal dromedary model, of the following form.

$$A = 1 - a \times \sin\left[\left(\frac{2\pi}{24}\right) \times \left(h + 6 - h_{min}\right)\right] \quad (4)$$

where:

a - 0.08, a constant that expresses the amplitude with respect to the constant 1 (CIGR, 2002);

h - time of the day (hour);

$h_{min}$ - the time of the day with minimum activity after midnight (hour).

Total heat production data for both algorithms was adjusted for environmental temperature deviation from neutrality by using the equation 5.

$$THP_{corr,T} = 4 \times 10^{-5} \left(20 - T\right)^3 \quad (5)$$

where:

$THP_{corr,T}$ - correction factor for temperature on total heat production from the animals, based on the thermoneutral level of 20 $^{o}$C, non-dimensional;

T - indoor air temperature, $^{o}$C.

Contribution of $CO_2$ production from litter was accounted by multiplying the metabolic $CO_2$ production rate in both algorithms by a correction factor of 1.077, as suggested by Xin et al. (2009). In this study, the results obtained from the three sampling schemes were used as input to the two algorithms, resulting in four different test methods, which were compared to the reference method. The labels attributed to the four test methods are: Test method 1- sampling scheme 1 and algorithm 1; Test method 2 - sampling scheme 1 and algorithm 2; Test method 3 - sampling scheme 2 and algorithm 1 ; Test Method 4 - Sampling scheme 2 and algorithm 2.

**Reference method for the determination of building VR and statistical analysis**

The reference procedure for calculating VR of the MV barn in this study consisted of the summation of the flow rate through all the running exhaust fans. The flow rate of

the exhaust fans was calculated by measuring upstream air velocity via a hot wire anemometer (model 425, Testo ®, São Paulo, Brazil), with a specified measurement range of 0 ~ 2 m $s^{-1}$, resolution of 0.01 m $s^{-1}$ and accuracy of ± (0.03 m s-1 + 5% of the reading), and was factory calibrated. Measurements were taken at 16 traverse points evenly distributed across the fan's entrance area. Mean air velocity was then multiplied by the fan area to obtain fan VR. Because the flow rate through the exhaust fans can vary with barn static pressure, which was not monitored, every time a new stage of fans was activated, a new measurement of their flow rate was taken.

In order to assess how the reference measurement method for VR is related to each of the test methods, an analysis was performed with the software SAS 9.2®, that delineates agreement between each of the test methods and the reference method. Specifically, the agreement was assessed by regressing the difference between reference and test methods ($\Delta_{VR} = VR_{reference} - VR_{test}$) and the mean VR obtained by both methods ($\overline{VR_i} = [VR_{reference} + VR_{test}]/2$), where if the null hypothesis $H_o$ of $\Delta VR = 0$ cannot be rejected, there would be no difference between the two methods. This method was proposed by Altman and Bland (1983) and improved by Fernandez and Fernandez (2009), in which ΔVR is regressed on $\overline{VR_i}$ (equation 6).

$$\Delta VR = \beta_0 + \beta_1 \overline{VR_i} + \varepsilon_i \quad (6)$$

where:

$\Delta VR$ - $(VR_{reference} - VR_{alternative})$, $m^3h^{-1}bird^{-1}$;

$\beta_o$ - Y-intercept, a measure of systematic positive or negative bias, $m^3h^{-1}bird^{-1}$;

$\beta_1$ - slope, a measure of nonsystematic heterogeneous bias, non-dimensional;

$\overline{VR_i}$ - is the average of VR measured with reference and alternative method, $m^3h^{-1}bird^{-1}$;

$\varepsilon_i$ - independent normally distributed homogeneous random error, $m^3h^{-1}bird^{-1}$.

In equation 6, the intercept ($\beta_0$) and the slope ($\beta_1$) represent homogeneous and heterogeneous systematic bias, respectively. A test of significance for each coefficient was carried on with PROC REG in SAS to assess if the systematic bias is statistically different than zero.

Next to the measure of estimated bias, attention was also be given to the nature of the random error in the measurements provided by each test method. The magnitude of

the error was calculated as the standard error (SE) and the data set tested for non-uniform error distribution (Hopkins, 2000) with the Heteroscedasticity Test (HCT) in SAS. When the existence of non-uniformity was detected, the calculation of the adjusted SE (also called "white" error) for $\beta_0$ and $\beta_1$ was done through the option ACOV in the MODEL statement of PROC REG in SAS.

## Results and discussion

### Assessment of agreement between reference and test methods in the MVB

The regression lines for the comparison between reference and the four different test methods for measurement of VR are presented in figure 1. The plots show heterogeneous patterns in the spread of the data points along the measurement range for all four test methods, being that the points tended to spread further apart in the mid-range of the tested values. Evidence at the level of 95% confidence for the existence of heterogeneous spread of the random error can be seen in table 1. The results confirm the existence of heterogeneous error distribution for most of the test methods. As a reaction to that, the significance test for the coefficients in the regression represented by equation 5 was done with the corrected SEs ($SE_{\beta 0}$ and $SE_{\beta 1,}$ table 1) (Fernandez and Fernandez, 2009).

Regression results for the model in equation 5 for all four test methods can also be seen in table 1. The significance test for $\beta_0$ in equation 5 revealed that for all test methods, a systematic positive homogeneous error was present. A systematic underestimation of $CO_2$ production leads to an underestimation of ventilation rate (eq.1) and explains why the bias represented by $\beta_0$ had a positive nature, the lowest regressed intercept values were (1.1 ± 0.8) $m^3h^{-1}bird^{-1}$ for test method 3 and (1.4 ± 0.9) $m^3h^{-1}bird^{-1}$ for test method 4 (table 1). Potential reasons for the existence of systematic bias could be the models used to estimate the metabolic $CO_2$ production in the barn, which was based on empirical coefficients (either RQ for algorithm 1 or the constant rate of production of $CO_2$ in algorithm 2) for broiler breeds tested during the 90s or earlier, while the modern broilers have growth rates that are increasing over the years, consequently increasing animal metabolic rate, and thus producing more $CO_2$ (Xin et al., 2009).

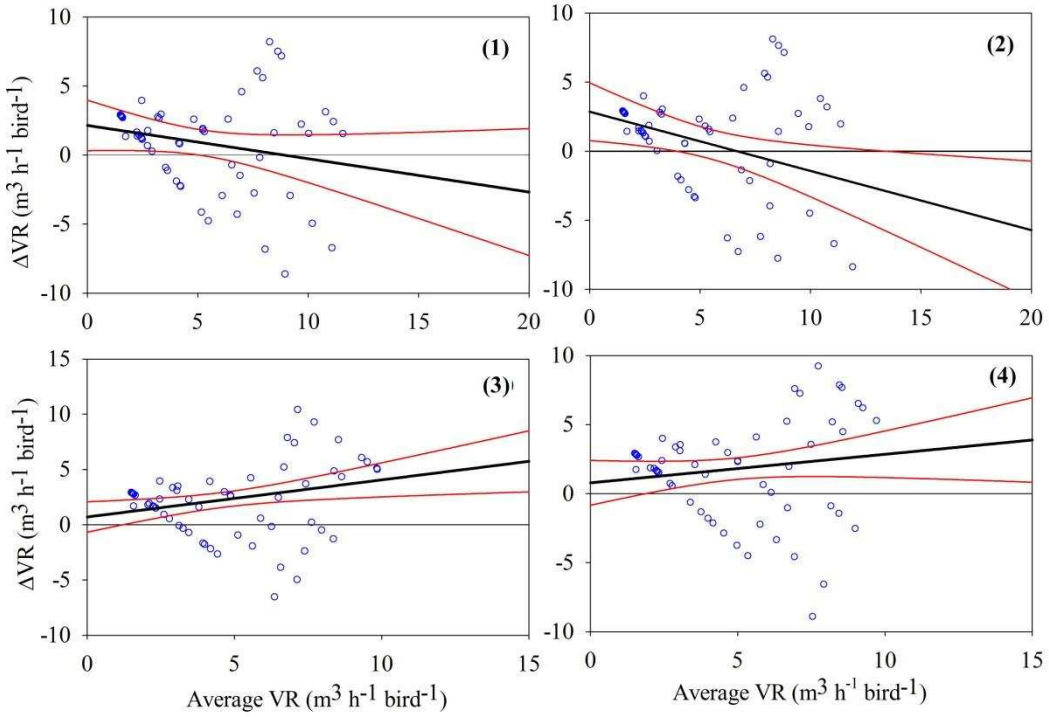


Figure 1. Plots for the difference between each of the alternative $CO_2$ balance methods for measuring ventilation flow rate (ΔVR) and the standard method against the average of the two methods ($\overline{VR}$ ) being compared. The four test methods are the combination of: (1) sampling scheme 1 and algorithm 1; (2) scheme 1 and algorithm 2; (3) sampling scheme 2 and algorithm 1; (4) Sampling scheme 2 and algorithm 2.

Table 1. Summary of statistics for the evaluation of agreement between reference and 6 test methods, by regressing data to the model $\Delta VR = \beta_o + \beta_1 \overline{VR}$

| **Test Method** | **1** | **2** | **3** | **4** |
|---|---|---|---|---|
| $\beta_0 \pm SE_{\beta_0}$, ($m^3\ h^{-1}\ bird^{-1}$) | 2.2* ± 0.5 | 2.9* ± 0.6 | 1.1* ± 0.8 | 1.4* ± 0.9 |
| $\beta_1 \pm SE_{\beta_1}$, (non-dimensional) | -0.2 ± 0.1 | -0.4 ± 0.2 | 0.2 ± 0.2 | 0.1 ± 0.2 |
| Adj. $R^2$ | 0.02 | 0.08 | 0.02 | 0.0099 |
| p-value for regression | 0.1270 | 0.0128 | 0.1405 | 0.5389 |
| n | 64 | 64 | 64 | 64 |

* Estimated coefficient is significantly different than zero at the level of 95% probability;

Calvet et al. (2011) suggested that the model for determination of VR from $CO_2$ balance for broiler litters should be adjusted with updated coefficients that account for both environmental temperature and modern strains of broilers that have been obtained by advances in genetics and improved feed composition. Havenstein et al. (2003) stated that broiler growth rate in terms of body weight (BW) increased by approximately 73 g

$yr^{-1}$ from 1976 to 1991, while increased BW means increase in metabolic rate, improved of feed conversion rate and consequently more release of $CO_2$ in an animal basis, along the years. Hence, it is necessary that new experiments be designed and performed on the quantification of the bioenergetics of the modern breeds of broilers in order to update and improve the metabolic $CO_2$ production estimates.

The significance test for $\beta_1$ indicated that the majority of test methods presented systematic heterogeneous bias that did not statistically differ from 0, presenting values that ranged from (-0.4 ± 0.2) to (0.2 ± 0.2) (table 1). This outcome indicates that systematic heterogeneous bias was nearly inexistent for any of the test methods.

Results of the non-linear regression analysis performed to adjust VR vs. $\Delta[CO_2]$ data from all test methods to the model in equation 7 can be seen in table 2. Empirical values obtained for the coefficient b for test methods 3 and 4 was (-0.9 ± 0.1), being significantly equal to -1 ($p < 0.0001$), indicating that these test methods present the best fit to the model. Hence, because tests methods 3 and 4 presented the lowest systematic bias while yielding the best fit with the theoretical model, they were regarded the most appropriate for application to the NV barn.

Table 2. Non-linear regression results for the fit of experimental and calculated data from the mechanically ventilated (MV) building to the model $VR = a\ \Delta[CO_2]^b$

| **Test method** | **Mean $\Delta[CO_2]$, ppm** | **a ± SE** | **b ± SE** | **Adj. $R^2$** | **Regression P-value** |
|---|---|---|---|---|---|
| 1 | 977 | 6273 ± 4383 | -0.6 ± 0.1 | 0.33 | < 0.0001 |
| 2 | 977 | 7828 ± 5948 | -0.6 ± 0.1 | 0.31 | < 0.0001 |
| 3 | 1015 | 1109 ± 718 | -0.9* ± 0.1 | 0.51 | < 0.0001 |
| 4 | 1015 | 1297 ± 899 | -0.9* ± 0.1 | 0.48 | < 0.0001 |

*the parameter estimate is not significantly different than the theoretical value of -1 at a confidence level of 95%.

The outcome that test methods 3 and 4 yielded in VR with the best fit to the reference method in the MV barn indicates that hourly changes in metabolic $CO_2$ production led to better estimates of VR (algorithm A2), as opposed to considering it constant thought out day and night periods (algorithm A1). On the other hand, the use of different sampling schemes (S1 and S2) between test methods 3 and 4 didn´t impact the estimates of VR from the MV barn, as compared to the reference method.

### Calculations of VR for the NVB with the best selected test methods

Calculated mean VR values by age for the NV barn, obtained with test methods 3 and 4 are presented in table 3 along with those obtained by Lacambra (1997), who recommended minimum, maximum VR values related to bird body weight. The VR data obtained with test methods 3 and 4 in this study compare well with those from Lacambra (1997), especially for the maximum recommended values.

**Table 3.** Data of bird body weight and ventilation rates (VR, $m^3\ h^{-1}\ bird^{-1}$) for broiler chickens as a function of bird age (d) presented by Lacambra, 1997 and calculated in this study for the naturally ventilated (NV) barn with test methods 3 and 4

| Bird age (wk) | Lacambra, 1997 | This study | |
|---|---|---|---|
| | | Test method 3 | Test method 4 |
| 1 | 0.3 | 0.8 ± 0.2 | 0.8 ± 0.2 |
| 2 | 0.8 | 2.0 ± 0.5 | 2.0 ± 0.4 |
| 3 | 2.1 | 1.6 ± 0.2 | 1.6 ± 0.2 |
| 4 | 4.3 | 2.1 ± 0.3 | 2.1 ± 0.3 |
| 5 | 7.5 | 4.1 ± 0.6 | 4.6 ± 0.7 |
| 6 | 11.5 | 8.1 ± 0.7 | 8.9 ± 0.8 |

The range of variability in VR by age for the NV barn calculated with test methods 3 and 4 are also presented in table 3 in terms of standard error of the mean (SE), going from 0.2 $m^3\ h^{-1}\ bird^{-1}$ to 0.7 $m^3\ h^{-1}\ bird^{-1}$ for ages 1 and 6 wk, respectively for test method 3 and from 0.2 $m^3\ h^{-1}\ bird^{-1}$ to 0.8 $m^3\ h^{-1}\ bird^{-1}$ for ages 1 and 6 wk, respectively for test method 4. The uncertainty associated to the use of the $CO_2$ mass balance for NVBs in livestock has been evaluated by Blanes and Pedersen (2005) for pig barns and by Samer et al. (2011) for dairy cow barns. One of the reasons for the relative variability appointed in most of these studies is the dependence on wind forces that cause both the concentrations to vary by a large extent and most importantly, causing the difference on $CO_2$ concentration between inside and outside barn ($\Delta CO_2$) to be small, which is when the $CO_2$ balance method should be used with care in naturally ventilated barns; Ouwerkerk and Pedersen (1994) suggested that $\Delta CO_2$ values shouldn't be lower than 200 ppm in order for the method to yield reliable results. In this study, more than 90% of the values for $\Delta CO_2$ used in tests methods 3 or 4 for the NV barn met the > 200 ppm criteria of Ouwerkerk and Pedersen (1994), ranging from 105 to 1596 ppm with mean and SE of (577 ± 34) ppm for both test methods.

## Conclusions

Four combinations of two sampling schemes and two sets of calculations were tested to measure the ventilation rate (VR) of a mechanically ventilated (MV) broiler barn based on the metabolic $CO_2$ mass balance method. The best test methods were selected in terms of presence of smallest systematic and heterogeneous bias, and were applied to calculate ventilation rate across a naturally ventilated (NV) broiler house. The following conclusions can be drawn:

1. Including variable animal activity throughout the day in calculations of metabolic $CO_2$ production combined with sampling $CO_2$ concentrations yielded the best estimates of VR for the MV barn as compared to the reference method;
2. There was no significant impact of the tested sampling schemes in the estimated VR calculated for the MV barn, as compared to the reference method.
3. Estimates of air flow rate for the NV barn were calculated by considering variable animal activity throughout the day and with measurements of $CO_2$ concentrations made above the animal occupied zone, with values ranging from $(0.44 \pm 0.04)$ $m^3$ $h^{-1}$ $bird^{-1}$ and $(10 \pm 1)$ $m^3$ $h^{-1}$ $bird^{-1}$ at the ages of 1 and 7 week.

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# CHAPTER 6. AMMONIA EMISSIONS FROM A NATURALLY AND A MECHANICALLY VENTILATED BROILER HOUSE IN BRAZIL

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A manuscript submitted to the Brazilian Journal of Agricultural and Environmental Engineering (AGRIAMBI)

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## Abstract

This study was conducted with the aim of monitoring ammonia ($NH_3$) emissions from a mechanically and a naturally ventilated (MV and NV, respectively) broiler house in the southeastern state of Minas Gerais and calculate their $NH_3$ emission factor ($f_{NH3}$). Bird stocking density was 13.5 and 11.1 birds $m^{-2}$ for the MV and NV barns, respectively. The marketing age was 43 d and bedding consisted of dried coffee husks in its first time of use. Ventilation rates were calculated with the metabolic carbon dioxide ($CO_2$) mass

balance method as elaborated by Pedersen et al. (2008). Values of $f_{NH3}$ were (0.32 ±0.10) g bird$^{-1}$ day$^{-1}$ and (0.27 ± 0.07) g bird$^{-1}$ day$^{-1}$ for the MV and NV barns, respectively, and are in agreement to what was presented in other studies performed under similar conditions. The statistical analysis indicated that the different types of ventilation systems didn´t have a significant impact on the parameters of the emission equation, being thus neglected in the modeling process. The $f_{NH3}$ estimated on yearly basis was 58 g bird-place$^{-1}$ year$^{-1}$. The results obtained with this study help providing reliable methodology for the determination of a solid database on $NH_3$ emission factors for tropical conditions that can be used for future inventories, when performed in a sufficient number of barns that is representative for the Brazilian scenario.

**Keywords:** emission factor, inventory, ventilation rate, tropical conditions

## Introduction

At global scale, Brazil is the third biggest producer and first ranked exporter of broiler chicken (MAPA, 2013). However, even with the considerable magnitude of animal production systems, very little effort has been given to estimate ammonia ($NH_3$) emission factors ($f_{NH3}$) from poultry houses under the unique Brazilian conditions: tropical climate and non-insulated broiler houses, that can be either mechanically ventilated (MV) or naturally ventilated (NV).

Studies on $NH_3$ emissions from confined animal operations such as broiler housing systems have been carried out around the world ever since at least 30 years. One of the outcomes of scientific research on $NH_3$ emissions from animal activity that have become a paradigm in the field is that excess $NH_3$ is in the atmosphere is detrimental to natural ecosystems (Galloway et al., 2008). The countries that first started their emissions studies are now at either of the following stages: (1) conducting emissions inventories, (2) developing mitigation techniques and (3) setting regulations. Emissions of $NH_3$ are still not legislated/regulated in Brazil, even though recent studies conducted in several parts of the world have evidenced changes in N sensitive ecosystems nearby areas that have intense livestock activity, pointing out the urgent need for implementation of mitigation strategies (Sutton et al., 2008).

In recent years, a few studies on $NH_3$ emissions conducted in Brazil have evidenced/demonstrated an increasing interest of the scientific sector on that issue. For instance, Miragliotta et al. (2004) reported one of the first studies on the development of a statistical model for $NH_3$ emissions from Brazilian broiler houses, based on correlation emissions with variables such as pH, environmental temperature and relative humidity; Lima et al. (2011) presented $NH_3$ emission factors for MV broiler barns under different litter conditions (new vs. used) combined with different stocking densities; Osorio (2010) developed a practical method for determining $NH_3$ emission rates in a NV Brazilian broiler barns; Souza and Mello (2011) presented an attempt of inventory of $NH_3$ emissions from all domestic animal categories over the state of Rio de Janeiro, however, using emission factors from studies performed in Europe and the U.S.A, and thus under temperate climate conditions. Some effort has also been given on the evaluation of mitigation strategies to reduce Brazilian $NH_3$ emissions, such as the study reported by Medeiros et al. (2008), who evaluated the effect of chemical additives to the litter as a means to reduce $NH_3$ volatilization.

However, given the magnitude and variability of Brazilian territorial area and poultry production, the number of studies dedicated to determine $NH_3$ emissions from this sector is insufficient/very limited. Furthermore, because the majority of the livestock barns in Brazil are naturally or semi-naturally ventilated, including most poultry barns (Menegali et al., 2013; Nazareno et al., 2009; Tinôco, 2001), specific methodologies for determination of $NH_3$ emission factors in these conditions must be developed, to strengthen the existent database on emission factors of this pollutant in Brazil.

Hence, this study was conducted with the purpose of simultaneously monitoring $NH_3$ emissions from a typical MV and also a typical NV Brazilian broiler houses. Specific objectives of this study were: (a) calculate $NH_3$ emission factor ($f_{NH3}$) from both studies MV and NV broiler houses; (b) compare $NH_3$ emission values obtained from this research with the results from other similar studies; and (c) evaluate the impact of the type of ventilation system in the estimates of $NH_3$ emissions.

## Material and methods

### Description of the barns, environmental control systems and birds' management

The study was conducted in two commercial broiler barns, one NV and the other MV, both located on the same farm in the state of Minas Gerais, Brazil. The MV barn had a dimension of 120.0 Length × 14.0 Width × 2.5 Side m (L × W × H), fiber-cement tile roof, and a polyurethane drop ceiling (the same material as used for the sidewall curtains). The sidewall curtains were closed most of the time, and the ventilation was provided with 8 newly installed exhaust fans (specified capacity of 39,329 $m^3$ $h^{-1}$ each at 1.5 HP and static pressure of 12.0 Pa) placed on the west end of the building. Fresh air was brought into the barn through air inlets located at the east end, and the inlet openings were adjusted manually, as needed. The ventilation program was based on indoor air temperature and consisted of 7 stages including minimum ventilation at the early age of the birds (< 3wk). The barn had an initial placement of 23,100 male Cobbs® chicks, and freshly dried coffee husks, serving as floor bedding, which was never used to raise broilers before. Chicks were reared up to marketing age of 43 day.

The NV barn had dimensions of 75 L × 12 W × 2.75 H m. It was roofed with ceramic tiles and polyurethane drop ceiling (same as used for sidewall curtains). Ventilation was provided through manual operation/opening of the sidewall curtains (fully open, half open, or nearly closed). The initial bird placement was 10,000 female Cobbs®, and had the same kind of non-used litter described for the MVB. This flock was also reared up to a marketing age of 43 day.

The lighting program was similar for both sex/barns and consisted of 1-hour dark between the ages 2 - 10 day; then the number of dark hours was increased to 9, and then decreased again to 8, 7 and 6 hours of dark at the ages of 22, 23 and 24 day, respectively. The light schedule then remained the same until bird age was 39 day, when the number of dark hours was set to 5, decreasing one hour a night till pick up day.

### Data collection procedures

Measurements of gaseous concentrations of $CO_2$ were performed in order to calculate air flow rate throughout the barns through the method proposed by Pedersen et al. (2008) with a hand-held sensor (model AZ 77535 $CO_2$/Temp/RH Meter, AZ Instrument Corp., Taichung City, Taiwan) that had a measuring range of 0 ~ 9999 $ppm_v$, resolution of 1 $ppm_v$ and accuracy of ± 30 $ppm_v$ ± 5% of the reading (according to

specifications, and calibrated at the factory). Concentrations of $NH_3$ were measured with an electrochemical detector "Gas Alert Extreme $NH_3$ Detector" (BW Technologies®, Oxfordshire, UK), with a measuring range of 0 ~ 100 $ppm_v$, operating temperature of -4 and 40°C, and accuracy of 2% (at 25°C and relative humidity between 15% to 90%). Both the $CO_2$ and $NH_3$ sensors were sent for calibration at the factory prior to the start of the study.

For the MV barn, background or outdoor $CO_2$ and $NH_3$ concentrations were measured at the inlet, i.e., nearby the east end of the building while indoors concentrations were measured at the outlet (upstream of the exhaust fans).

For the NV barn, indoors gaseous concentrations of $CO_2$ and $NH_3$ were measured at three different distances along the central axis of the building (at 18, 36 and 54 m from the eastern extremity of the barn), and at two different heights (0.50 and 1.25 m above the litter). Outdoors concentrations were measured at three different points along the south side of the building, which was considered the air inlet, as it was observed that when the data was being collected, the wind was consistently coming from the south.

Data collection of concentrations of $CO_2$ and $NH_3$ was done once every three hours, for a 48-hour period, performed weekly throughout the 7–week grow-out period. Monitoring of concentrations in different points within the barn was not done simultaneously, but collected within a 15 min interval (as quick as possible) for each barn.

**Calculations of ventilation rates and ammonia emission rates**

Building ventilation rate was estimated through Eq. 1(Pedersen et al., 2008).

$$Q = \frac{A \times (CO_2)_{metabolic} + (CO_2)_{litter}}{\Delta[CO_2]} \quad (1)$$

where

VR - the building ventilation flow ($m^3\ h^{-1}\ hpu^{-1}$);

A - the relative animal activity (non-dimensional);

$(CO_2)_{metabolic}$ - metabolic $CO_2$ production by the animals ($m^3\ h^{-1}\ hpu^{-1}$);

$(CO_2)_{litter}$ - the $CO_2$ released by the litter ($m^3\ h^{-1}\ hpu^{-1}$);

$\Delta[CO_2]$ - $[CO_2]_{indoors}$ - $[CO_2]_{outdoors}$, the indoor and outdoor $CO_2$ concentrations, respectively (ppm).

Ventilation rates in $m^3$ $day^{-1}$ $hpu^{-1}$ were then converted in $m^3$ $day^{-1}bird^{-1}$ by using the conversion factor proposed by Pedersen et al. (2008) of 1 hpu (heat production unit) as 1000 W of total heat at 20°C. Additionally, a correction factor for metabolic $CO_2$ production was made with temperature measurements made in the barns. A more detailed algorithm for the calculation of Q for both buildings was developed and described in the work presented by Mendes et al. (2012).

Daily $NH_3$ ER was calculated with the following equation:

$$NH_3ER = \frac{Q \times \Delta[NH_3] w_{NH_3}}{V_{NH_3}} \quad (2)$$

Where:

- Q - the building ventilation flow ($m^3$ $day^{-1}bird^{-1}$);
- $NH_3ER$ - ammonia emission rate in g $bird^{-1}$ $day^{-1}$;
- $\Delta[NH_3]$ - $[NH_3]_{indoors}$ - $[NH_3]_{outdoors}$, the averaged indoor and outdoor $NH_3$ concentrations, respectively ($ppm_v$);
- $W_{NH3}$ - molecular weight of $NH_3$ (17.031 g $mol^{-1}$);
- $V_{NH3}$ - molar volume of $NH_3$ at standard temperature (25°C) and pressure (1 ATM) (0.0245 $m^3$ $mol^{-1}$).

## Data handling and statistical analysis

The mean difference between daily $NH_3ER$ data from the MV and the NV barns obtained simultaneously (measured at the same bird age) was tested with the procedure proc ttest in SAS®. The objective of the use of t-test was to test the hypothesis that the mean difference between $NH_3ER$ from both barns is significantly different from zero.

Furthermore, an analysis of variance was performed in two different levels to test the explanatory power of two models in predicting $NH_3ER$. The first level consists of a simpler or reduced model, which describes $NH_3ER$ as a function of bird age only, in which data sets from both types of barns were pooled together and the model is represented by Eq. 3. For the second level, a more complex, or full model is tested, in which the type of barn was included with the development of one regression equation for each, the MV and NV barns, represented by Eq. 4 and Eq. 5, respectively.

Reduced model:

$$NH_3ER = \beta_0 + \beta_1 \cdot x + \beta_2 \cdot x^2 \quad (3)$$

Full model:

$$NH_3ER_{MV} = \beta_{0,MV} + \beta_{1,MV} \cdot x + \beta_{2,MV} \cdot x^2 \quad (4)$$

$$NH_3ER_{NV} = \beta_{0,NV} + \beta_{1,NV} \cdot x + \beta_{2,NV} \cdot x^2 \quad (5)$$

where:

| | | |
|---|---|---|
| $NH_3ER_{MV}$, $NH_3ER_{NV}$ | - | the building ventilation flow ($m^3$ $h^{-1}$ $hpu^{-1}$); |
| X | - | Bird age (d); |
| $ß_0$, $ß_1$, $ß_2$, $ß_{0,MV}$, $ß_{1,MV}$, $ß_{2,MV}$, $ß_{0,NV}$, $ß_{1,NV}$ and $ß_{2,NV}$ | - | Empirical coefficients obtained by regression analysis. |

The ANOVA was performed for each model using the procedure proc glm in SAS®. In order to test whether the extra degrees of freedom included in the full model has a significant impact on the estimate of $NH_3ER$, an extra sum of squares test (Ramsey and Schafer, 2002) was performed from the ANOVA output obtained from each model. Additionally, an analysis of regression was performed with proc reg in SAS® for the determination of model coefficients.

With the adjusted equation, cumulative $NH_3$ emission data was calculated throughout the year using a methodology similar to that of Gates et al. (2008), by incorporating downtime between flocks and variation in days to achieve market weight, mimicking the effect of multiple flocks in the same barn.

## Results and discussion

### Determination of daily $NH_3$ emission factors

Mean $f_{NH3}$ obtained from the MV and NV barns were (0.32 ± 0.10) g $bird^{-1}$ $day^{-1}$ and (0.27 ± 0.07) g $bird^{-1}$ $day^{-1}$, respectively, and are also presented in table 1. The results of the paired t-test indicated that the mean difference in daily $NH_3ER$ measured in the MV and NV barns, was (0.05 ± 0.07) g bird $day^{-1}$ and was not significantly different from zero (p=0.394). This outcome suggests that for the studied MV and NV barns, the use of different ventilation systems (mechanical vs. natural) when combined with different stocking density allocations (13 and 11 birds $m^{-2}$) didn´t allow for different emission rates, either in a per bird or per day basis.

Table 1. Ammonia emission factors ($f_{NH3}$) estimated from this study and other studies

| Reference[1] | Type of ventilation system | $NH_3ER$ (mean ± SE[2], g bird$^{-1}$ day$^{-1}$) | Local |
|---|---|---|---|
| This study | Mechanical | 0.32 ± 0.10 | MG/Brazil |
| This study | Natural | 0.27 ± 0.07 | MG/Brazil |
| Osorio (2010) | Natural | 0.28 ± 0.16 | MG/Brazil |
| Lima et al. (2011) | Mechanical | 0.78 | SP/Brazil |
| Burns et al. (2007) | Mechanical | 0.47 | KY/USA |
| Wheeler et al. (2006) | Mechanical | 0.63 | KY & PN/USA |
| (Groot Koerkamp et al., 1998) | Mechanical | 0.21 - 0.47 | Northern Europe[3] |

[1]For comparison purposes, only broiler barns with new litter were considered; [2]Standard error of the mean; [3]Denmark, England, Germany and the Netherlands.

The daily $f_{NH3}$ obtained from similar studies performed in Brazil and abroad are also presented in table 1. Unfortunately, not all the emission factors presented in all of the considered studies were not accompanied by an uncertainty estimate, such as a standard error (SE), what makes it difficult to draw comparisons. The emission factor presented by Lima et al. (2011) of 0.78 g bird$^{-1}$ day$^{-1}$ was relatively higher than the ones presented in this study, even though that monitoring performed by those authors also took place in Brazil. The difference might be due to the fact in the study of Lima et al. (2011), the broiler barns were ventilated with lower mean ventilation rate; lower levels of air exchange rate enhance conditions for $NH_3$ volatilization from litter in mechanically ventilated barns, causing, thus, an increase in emission rates. As for a comparison with the $f_{NH3}$ obtained by Osorio (2010), in a study performed inside a NV barn, the value of (0.28 ± 0.16) g bird$^{-1}$ day$^{-1}$ was comparable with the values obtained for both barns of this study, this similarity might be due to the fact that the broiler barns from both studies were located in the same state, and presumably having the similar types of management, and feed protein content.

As for the comparison of $f_{NH3}$ obtained in this study with those obtained in the U.S.A and northern Europe, data in table 1 indicate that the values obtained from two American studies (Burns et al., 2007; Wheeler et al., 2006) are considerably higher (0.47 g bird$^{-1}$ day$^{-1}$ and 063 g bird$^{-1}$ day$^{-1}$, respectively). However, data from this study seems to fit well with those presented by Groot Koerkamp et al. (1998) for four northern European countries (Denmark, England, Germany and the Netherlands), varying from 0.21 g bird$^{-1}$ day$^{-1}$ to 0.47g bird$^{-1}$ day$^{-1}$. It is speculated that the emission factors for the U.S.A. are considerably higher than that of Northern Europe and the ones obtained in this study potentially because of the use of very high protein content feed

administered to the animals, while in European farmers are subjected to emission ceilings imposed by progressively restrictive regulations that started to be implemented in the beginning of the 1990s.

### Simulations of yearly $NH_3$ emission factors

The results of the regression analysis performed for reduced and full models are presented in table 2. The calculated F-statistics were higher than the critical F-values for both models at a significance level of 1%, suggesting that both models presented good fit to the experimental data.

Table 2. Results from analysis of variance (ANOVA) for the regression of $NH_3$ emission rate ($NH_3$ER, g bird$^{-1}$ day$^{-1}$) as a function of bird age (x, day) only (reduced model); the regression of $NH_3$ emission rate against bird age and type of barn (NV or MV) (full model)

| Parameter | Degrees of freedom | Sum of squares | Mean sum of squares | F |
|---|---|---|---|---|
| Reduced model | 3 | 6.8741 | 2.2914 | 59.83** |
| Residual | 111 | 4.2490 | 0.0383 | |
| Total | 113 | 11.1231 | | |
| Full model | 6 | 7.0477 | 1.1746 | 32.01** |
| Residual | 111 | 4.0695 | 0.0367 | |
| Total | 113 | 11.1172 | | |

** the calculated F-statistic is higher than the critical F-statistic from a F distribution table (Ramsey and Schafer, 2002) at a significance level of 1%.

The test of significance for the coefficients $ß_o$, $ß_1$ and $ß_2$ in Eq. 3 and indicated that all of them are significantly different than zero (p-value < 0.001), and results are presented in table 3. A comparison of the estimates of the coefficients obtained for data from the MV and NV barns (full model) suggest that they are relatively similar to those obtained from the pooled data set (reduced model). For instance, the estimated values for the coefficient respective to the independent term, $y_o$, were (-4.0 ± 0.6) g bird$^{-1}$day$^{-1}$ and (-3.2 ± 0.6) g bird$^{-1}$day$^{-1}$, for the MV and NV barns, respectively, while that obtained from the pooled data sets was (-3.5 ± 0.4) g bird$^{-1}$day$^{-1}$. The estimated coefficient for the squared term ($x^2$) in Eq. 3 was (-0.0040 ± 0.0006) g bird$^{-1}$day$^{-3}$ and (-0.0028 ± 0.0006) g bird$^{-1}$day$^{-3}$, for the MV and NV barns, respectively, against (-0.0034 ± 0.0004) g bird$^{-1}$day$^{-3}$, obtained when neglecting the type of ventilation system. The similarity between the regression models obtained with the regression for MV and NV

barns can be seen with the plots shown in fig. 1 (left), and regression curve respective to the pooled data sets is presented in fig. 1 (right).

Table 3. Results from analysis of variance (ANOVA) for the relationship between bird age (x, d) and $NH_3$ emission rate ($NH_3ER$, g $bird^{-1}$ $day^{-1}$), according to the type of model (reduced of full)

| Parameter* | $ß_0$ (g $bird^{-1}$ $day^{-1}$) | $ß_1$ (g $bird^{-1}$ $day^{-2}$) | $ß_2$ (g $bird^{-1}$ $day^{-3}$) |
|---|---|---|---|
| Reduced model | -3.5 ± 0.4 | 0.24 ± 0.03 | -0.0034 ± 0.0004 |
| Full model: MV | -4.0 ± 0.6 | 0.27 ± 0.04 | -0.0040 ± 0.0006 |
| Full model: NV | -3.2 ± 0.6 | 0.21 ± 0.04 | -0.0028 ± 0.0006 |

*all coefficient estimates were significantly different than zero at a confidence level of 95%.

The negative sign of the coefficient indicates that the daily $NH_3ER$ increases with bird age, reaching a maximum, and starts to decrease. The behavior of increasing $NH_3ER$ with increase in age can be explained by the fact that the manure accumulated in the new litter gradually starts to release $NH_3$. However, the sudden increase in ventilation rate that happened when the birds reached the fifth week of age, as an attempt to keep thermoneutrality conditions in the barns (fig. 1), presumably causing litter moisture content to decrease with consequent reduced volatilization of $NH_3$, and thus reducing $NH_3ER$.

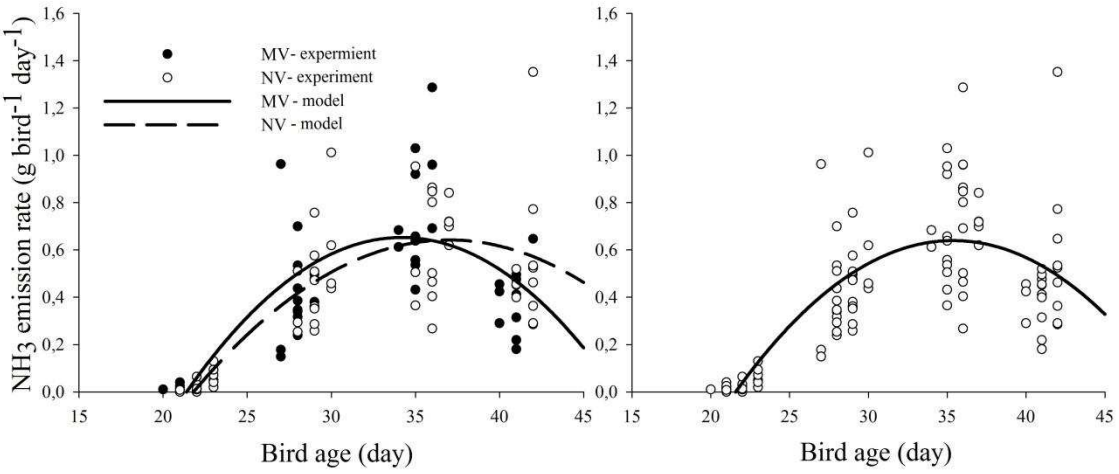


Figure 1. Relationship between bird age (d) and $NH_3$ emission rate ($NH_3ER$, g $bird^{-1}$ $day^{-1}$) for both the mechanically and naturally ventilated barns (MV and NV barns, respectively) (left) and obtained from pooling data for both types of barns (right).

Additionally, the results of the extra sum of squares test, performed to compare full and reduced models are presented in table 4, and indicate that the models are not significantly different in predicting $NH_3ER$, with a calculated F-statistics (1.55) that is less than the critical F-value (>3.95). This outcome suggests that the extra complexity represented by the full model with the inclusion of the factor 'type of barn' didn´t make the model fit better than the reduced to $NH_3ER$ data. For this reason, the full model was discarded and further data analysis and discussion in this paper were done with the data sets from MV and NV barns pooled together.

The adjusted model obtained for the relationship between daily $NH_3ER$ and bird age for the pooled data sets from MV and NV barns were used to calculate cumulative $NH_3$ emissions throughout an entire cycle of 43 days, and the results are graphically represented in fig. 2, a similar procedure was performed by Gates et al. (2008) for broilers housed mechanically ventilated barn with litter of first use and stocked at 15 birds $m^{-2}$, whose results are also included in fig. 2.

Table 4. Results from the extra sum of squares test that was performed on the additional degrees of freedoms included by the full model when compared with the reduced model

| Parameter | Degrees of freedom | Sum of squares | Mean sum of squares | F |
|---|---|---|---|---|
| Full vs. Reduced models | 3 | 0.1795 | 0.0598 | $1.55^{ns}$ |
| Residual | 110 | 4.2490 | 0.0386 | |
| Total | 113 | 4.4285 | | |

** the calculated F-statistic is higher than the critical F-statistic from a F distribution table (Ramsey and Schafer, 2002) at a significance level of 1%.

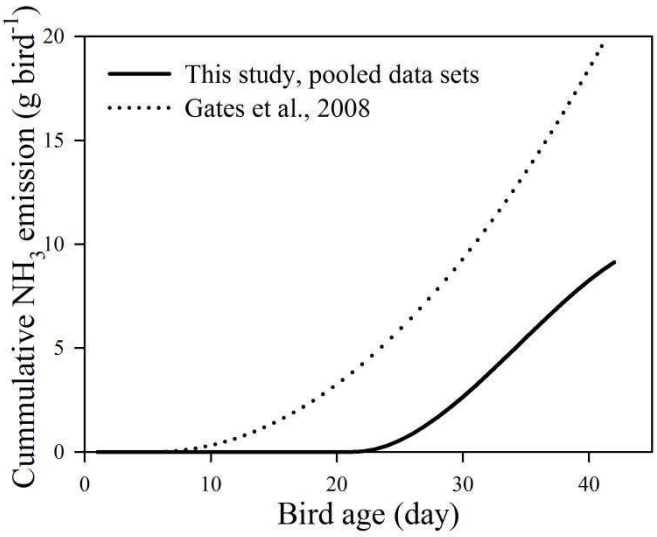


Figure 2. Modeled cumulative $NH_3$ emission (g bird-1) as a function of bird age) for data combined from both the mechanically and naturally ventilated barns.

The observation of the curves in fig.2 suggests that the increase in cumulative $NH_3$ emissions throughout a complete rearing cycle of 43 days for the barns used in the current study are relatively lower as compared to that of the study performed by Gates et al. (2008). It is speculated that the difference might be due to factors that play an important role on $NH_3$ emissions such as distinct feed protein content, mean barn ventilation rate and different litter material.

In order to estimate $f_{NH3}$ in a yearly basis for the barns monitored in this study, cumulative emissions from multiple flocks throughout a year were calculated using the adjusted equation that resulted from the pooled data set, with coefficients shown in table 3. In order to comply with the sanitary safety period between flocks, a gap of 14 day between flocks was used. It was assumed that at the start of every flock, only new litter was used, meaning that no $NH_3$ was emitted during the 14 day sanitary safety period. Similar calculations were performed with data presented by Gates et al. (2008). A graphical representation of the simulated cumulative $NH_3$ emissions is presented in fig. 3.

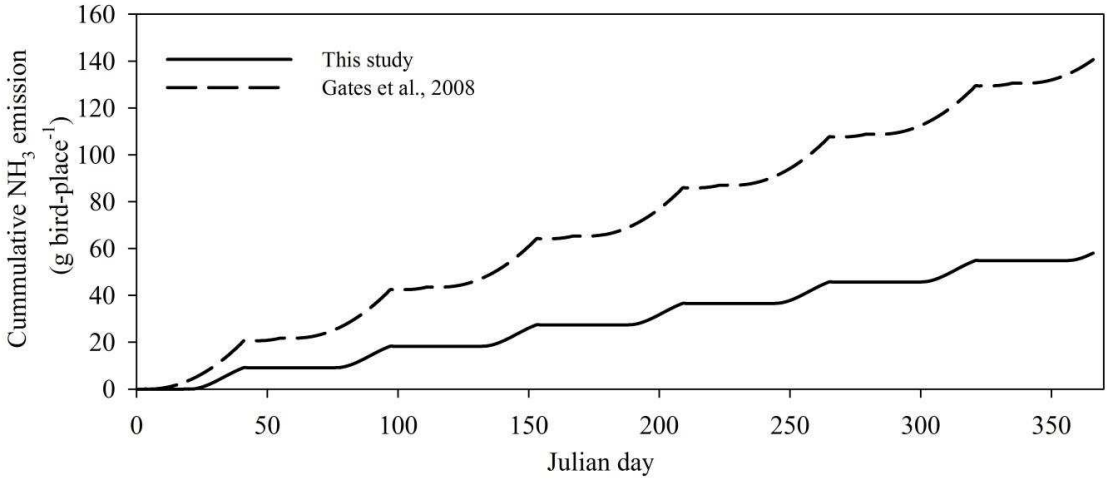

Figure 3. Cumulative ammonia emission over a year, from multiple flocks, averaged for the barns monitored in this study, assuming a resting period between flocks of 14 day.

Simulated $f_{NH3}$ on yearly basis were 58 g bird-place$^{-1}$ year$^{-1}$, while the $f_{NH3}$ simulated from the study of Gates et al. (2008) was 141 g bird-place$^{-1}$ year$^{-1}$. The discrepancy with the yearly $f_{NH3}$ obtained in this study with that from Gates et al. (2008) might have arisen from factors such as differences in farm management, feed protein content offered to the birds and/or distinct mean ventilation rate. Winkel et al. (2011) arrived at (72 ± 25) g bird-place$^{-1}$ year$^{-1}$, averaged from several monitored mechanically ventilated broiler barns in the Netherlands, this value is much closer to the one obtained in this study than the one obtained from Gates et al. (2008), for the U.S.A. From these results, it is speculated that northern American commercial broilers are fed with very high protein content feed formulas, and the northern European countries, such as the Netherlands, have been implementing feed manipulation techniques to reduce $NH_3$ emissions as explained before in this paper.

Another important aspect brought up by the study of Winkel et al. (2011) in the calculation of $f_{NH3}$ was the inclusion of a standard deviation to estimate the emission uncertainty between barns. According to Ogink et al. (2008), including a spatial variability factor (uncertainty between farms) in the determination of $f_{NH3}$ is just as important as considering variability due to seasonal or distinct management system (uncertainty within farm). Hence, it is recommended that the methodology described here be applied to barns located in different farms, so that a measure of uncertainty amongst farms can be included in the calculation of $f_{NH3}$.

## Conclusions

1. The method for determination of $NH_3ER$ applicable to both barns, with the ventilation rates being calculated through the carbon dioxide mass balance method, was successful;
2. Estimated values of $f_{NH3}$, on a daily bases, were (0.40 ± 0.12) g $bird^{-1}$ $day^{-1}$ and (0.32 ± 0.08) g $bird^{-1}$ $day^{-1}$ for the MV and NV barns, respectively, and was comparable to the results indicated by other literature sources;
3. The types of ventilation system didn´t have a significant impact on the parameters of the $NH_3$ emission equation, being thus discarded in the modeling;
4. Simulated value of $f_{NH3}$, on yearly basis, was 58 g $bird\text{-}place^{-1}$ $year^{-1}$;

## Acknowledgements

The authors would like to acknowledge the Brazilian government research fomenting agencies: CNPq (National Council for Research and Development), CAPES (National Council for Improvement of Highly Educated Personnel) and FAPEMIG (Foundation for Support of Scientific Research in the State of Minas Gerais).

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# CHAPTER 7. FINAL SUMMARY

This thesis attempts to cover a number of questions and concerns regarding the current available means to measure emissions and air flows from naturally ventilated (NV) livestock buildings. The five papers include a variety of factors and implications related to a NV dairy cow barn in the Netherlands and a NV broiler barn in Brazil. The following is a summary of the findings and conclusions from the studies.

1. In the first paper, a commercially available low-cost Non-Dispersive Infra-Red (NDIR) sensor was compared with two commonly applied methods, a Photo-Acoustic Spectroscopy (PAS) Gas Monitor and an Open-Path laser (OP-laser). The main purpose was to evaluate the suitability of the NDIR sensors for intensive spatial and temporal field monitoring of carbon dioxide ($CO_2$) concentrations in a NV dairy cow house. The NDIR sensors turned out to be a feasible alternative to monitor single-point or averaged spatial $CO_2$ concentrations in livestock barns by presenting a small variability between sensors of 5%, sensitivity to static pressure of 0.08% of the reading per each 1hPa, and yields field measurements with an average uncertainty of 9 %. The results also indicated that the NDIR sensors can be calibrated either in field or laboratory sensors for multi-point monitoring of $CO_2$ concentrations in NV livestock barns. The tested sensors were considered as reliable as the PAS and the OP-laser methods.
2. The second paper was prepared in the context of using the tracer gas method to estimate emissions from NV livestock buildings. In the cases where the tracer gas method is applied, accurate measurement of the tracer release rate ($Q_T$) and a representative estimate of the mixing ratio between pollutant (P) and tracer (T) gases ($\overline{[P]/[T]}$) are necessary. Hence, the main objective of that study was to assess the spatial variability of concentrations of the artificial tracer gas sulfur hexafluoride ($SF_6$), the natural tracer $CO_2$ and the pollutant ammonia ($NH_3$), along with their mixing ratios ($[NH_3]/[CO_2]$, $[NH_3]/[SF_6]$, $[CO_2]/[SF_6]$), inside a NV dairy cow barn. The results indicated that the vertical variability of the calculated mixing ratios became more stable with increase in height, reaching approximately constant values above the Animal Occupied Zone (AOZ, V > 2

m). Using both the naturally produced $CO_2$ and the artificially injected $SF_6$ as a tracer gas led to a homogeneous spread in behavior of mixing ratios along vertical and cross horizontal directions. Another important finding of this study was that, in the conditions in which it was carried on, the best place to sample P and T concentrations and mixing ratios is above the AOZ.

3. The third paper was about the development and validation a computer model of the studied Dutch NV dairy cow barn with the help of Computational Fluid Dynamics (CFD). The model, which is still being developed, is designed to assess the combined use of a CFD model and a metabolic $CO_2$ production model to predict air flows and $CO_2$ distribution in the ventilated airspace of the barn. With the model, the zone within the barn occupied by the cows were implemented as porous domain, generating heat and $CO_2$ in order to mimic animal activity. For a validation of the model, $CO_2$ concentration data from 15 NDIR $CO_2$ sensors, installed on a horizontal plane 3 m above the slats, was compared to the concentrations predicted by the model. The preliminary results of the simulations performed with the model indicated that it is a suitable means to understand the air and $CO_2$ motion patterns within the ventilated airspace, and presented a Normalized Mean Square Error (NMSE) of 0.053, which indicates that the model is a good predictor of barn´s $CO_2$ concentrations.
4. The objectives of the work described in the fourth paper were to evaluate four relatively simple protocols for use in NV broiler barns in Brazil. The test protocols were first evaluated with a mechanically-ventilated (MV) broiler barn by comparing its ventilation obtained from $CO_2$ mass balance with the VR measured using fan traverse, and the best ones were used to calculate VR in the NV barn, where the reference method could not be applied. The tested methods consisted of combinations between two different sampling schemes and two algorithms for prediction of metabolic $CO_2$ production rate from the birds. The results demonstrated that incorporation of diurnal animal activity in calculation of metabolic $CO_2$ production combined with sampling $CO_2$ concentration near AOZ yielded the best estimate of building ventilation rates. The evaluated protocol represents a simple and effective mean to determine air flow rate in naturally ventilated broiler barns that does not require the use of sophisticated instruments or intensive data acquisition.

5. In the last presented paper, $NH_3$ emissions were monitored from a MV and NV broiler house in Brazil. The methodology for calculation of emission rates was the best one determined in the previous paper. The estimated $NH_3$ emission factors ($f_{NH3}$) were (0.32 ±0.10) g bird$^{-1}$ day$^{-1}$ and (0.27 ± 0.07) g bird$^{-1}$ day$^{-1}$ for the MV and NV barns, respectively, and are in agreement to what was presented in other studies performed under similar conditions. The $f_{NH3}$ estimated on yearly basis was 58 g bird-place$^{-1}$ year$^{-1}$, average for both barns.

Overall, this thesis proves that despite the complications related to monitor air and gaseous pollutant flows through NV buildings, emission factors that are comparable to those obtained from MV barns are likely to be obtained. However, a few crucial aspects related to monitoring emissions from NV barns may be considered. The lack of a constant outlet in NV buildings, makes it necessary to perform sampling of gaseous concentrations in multiple points spread across the NV barn. Hence, focus should be given to finding suitable gaseous concentration monitoring devices, perhaps of lower prices, for multiple spatial monitoring, instead of concentrating most of the efforts in very accurate and costly methods that can only monitor in a few positions. The tracer gas technique seems to be the most appropriate method for monitoring emissions from NV livestock barns. When this method is applied, there is no need to estimate barn ventilation rates. Even though with the obvious differences between the Dutch NV dairy cow and Brazilian NV broiler barns, the results presented throughout this thesis indicated that the approach is similar. Sampling strategies can be translated from one type of housed animal category to another.

## ATTACHMENTS

## Attachment I: Regression lines and Bland-Altman Plots for the combination of different numbers of NDIR sensors and different MIT

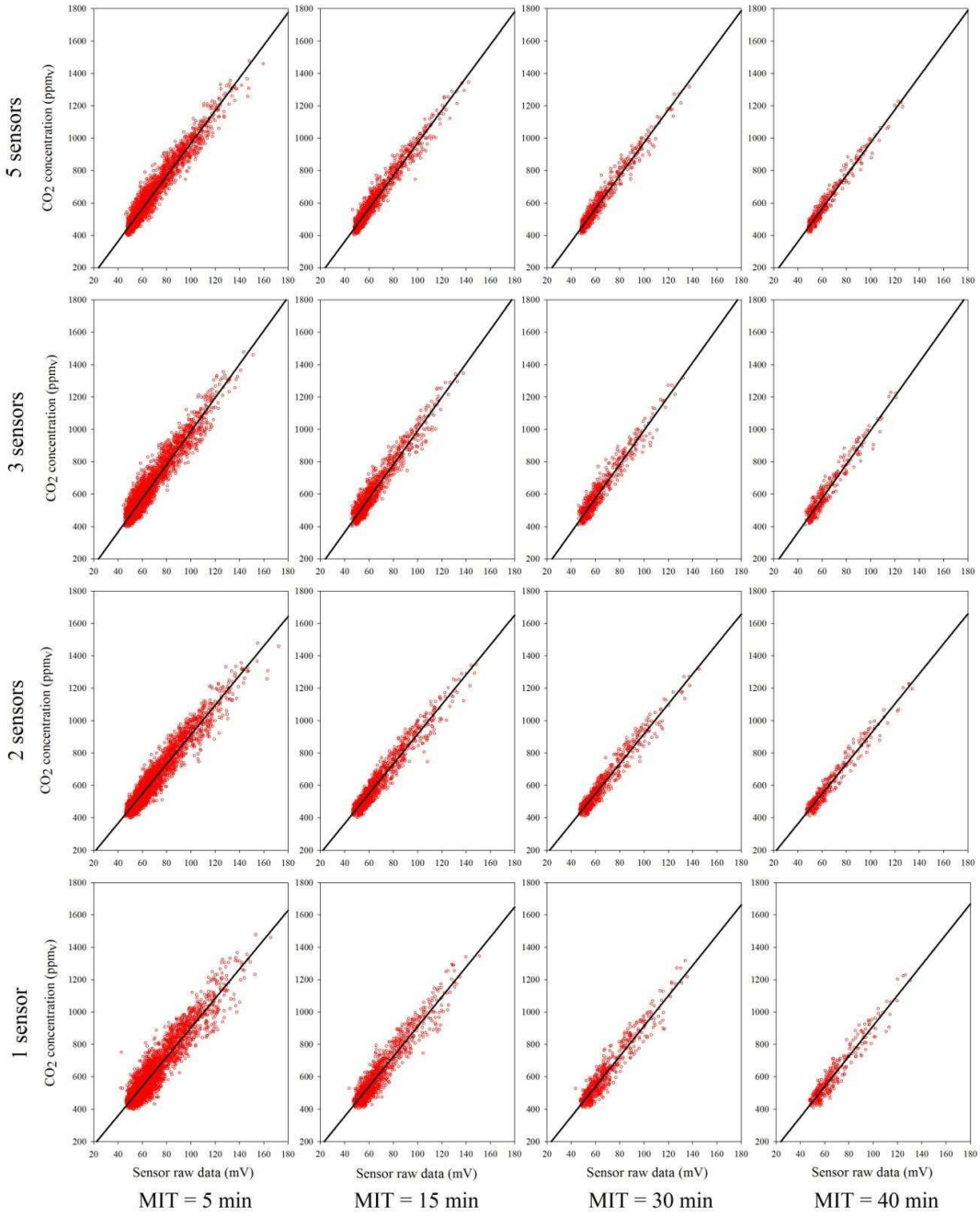


Figure 1. Relationship of $CO_2$ concentrations ([$CO_2$], $ppm_v$) measured with the OP-laser and averaged raw data (mV) from different numbers of NDIR sensors at different mean integration times (MIT, min).

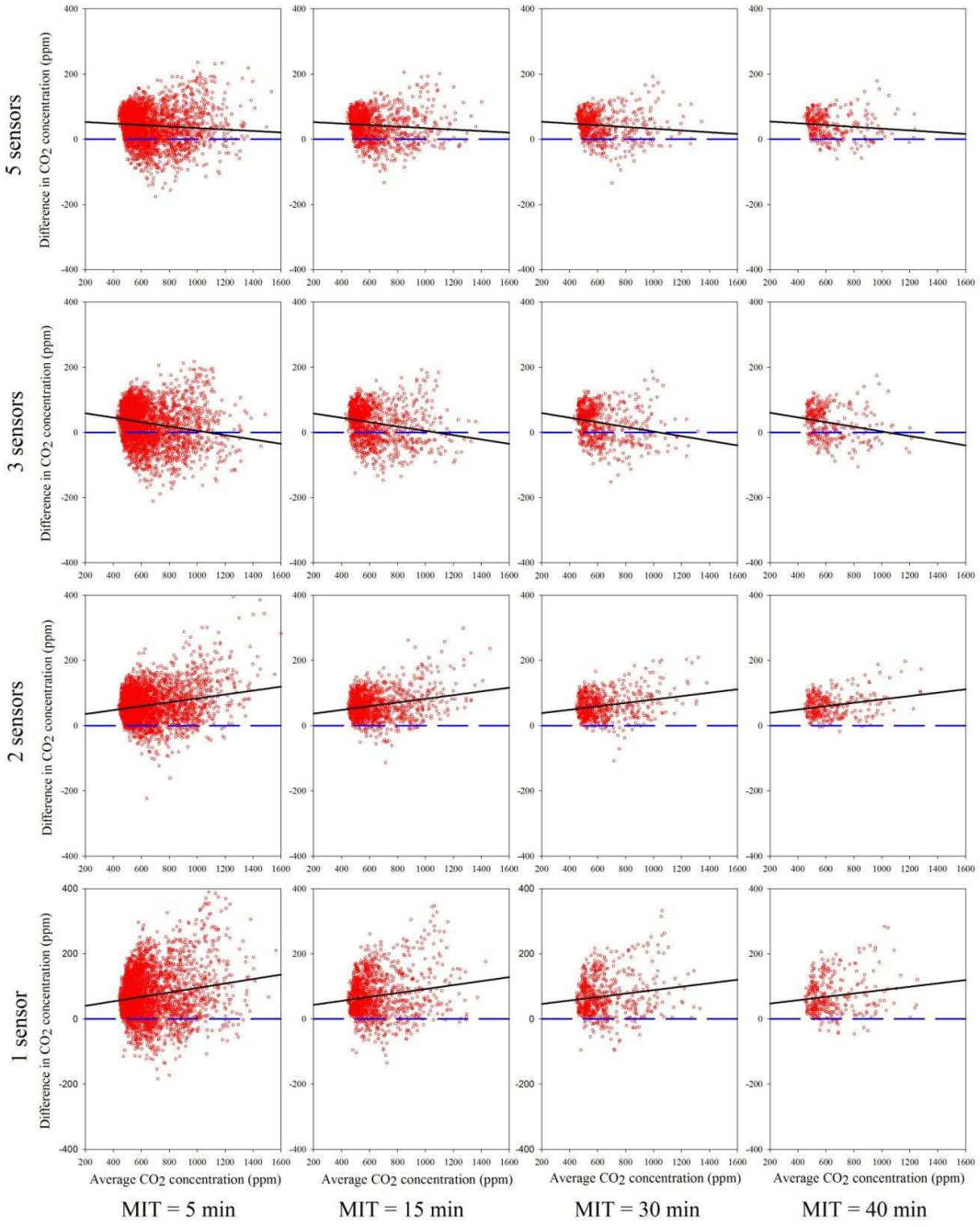


Figure 2. Bland-Altman charts for the relationship of $CO_2$ concentration determined through field calibration with the OP-laser and the laboratory calibrated NDIR sensors, at different mean integration times (MIT) and using different number of NDIR sensors to estimate average concentration. The concentrations in X - axis are obtained by averaging out values obtained from field and laboratory calibrations.

## Attachment II: Development of the differential equation for the constant rate of release of the tracer gas

The theoretical foundation for tracer gas research is provided by the mixing-dilution first degree differential equation described as Equation 1 .

$$V\frac{dC}{dt} = Q\left(\left[T\right]_e - \left[T\right]_i\right) \quad (1)$$

Where V is the volume of the ventilated airspace; Q is the building ventilation rate; and $[T]_e$, $[T]_i$ are concentrations of a given tracer at exhaust and inlet, respectively.

A solution for the above differential equation, proposed by , is obtained by evaluating its integral, considering a constant injection of the tracer ($Q_T$) and measuring building average gaseous concentration of the tracer ($\left[\overline{T}\right]$), the solution yields in equation 2.

$$Q = \frac{Q_T}{\left[\overline{T}\right]} \quad (2)$$

Equation 2 can be actually applied to any gas being released in the building that presents properties similar to those of T, such as a gaseous pollutant (P). In other words, Q is proportional, to the ratio between the rate of release of any pollutant gas P in the building ($Q_P$) and its average concentration $\left[\overline{P}\right]$. Hence, equation 2 can be rewritten as equation 3 below.

$$Q = \frac{Q_T}{\left[\overline{T}\right]} = \frac{Q_P}{\left[\overline{P}\right]} \quad (3)$$

The equation above suggests that once the rate of release of the tracer T ($Q_T$) is known, and both tracer and pollutant are well mixed in the ventilated airspace, the emission rate of P can be expressed as a ratio between T and P, as shown in equation 4.

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