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ACKNOWLEDGMENTS

I wish to thank my major professor, Dr. Pius Ndegwa, from the deepest of my heart for his consistent support, guidance and encouragement that has made my learning experience throughout my graduate studies very rewarding and satisfying.

I also thank all of my committee members, Dr. Claudio Stöckle, Dr. Joe Harrison, and Dr. Heping Liu, for their valuable suggestions and professional guidance on the development and completion of this dissertation and journal publications originating from this work.

My special-thank you also go to many people for their valuable expert guidance. To Dr. HungSoo Joo, thank you so much for generously providing invaluable mentorship and research support. Thank you Dr. Kedar Koirala for your advice towards my research direction. Thank you Mr. Jonathan Lomber for your assistance in the laboratory. I also want give thanks to Dr. Liang Yu, Yulong Ma and all my classmates for their valuable inputs, contributions and friendship. Many thanks are also extended to Pat Huggins, John Anderson, Joan Hagerdorn, Dorota Wilk, Joanna Dreger, and Dr. Roger Nelson, for your laboratory and administrative support.

My deepest gratitude goes to my parents, my husband Jingwei and kids: Richie and Riley as well. Your unconditional love and unending support gave me the strength to complete my PhD program.

Finally, I would like to express my sincere gratitude to all the other people (whose names I may have missed) that contributed to the completion of this thesis. You all made living and studying in Washington State University a great and memorable experience!
Agriculture contributes over 80% of national \( \text{NH}_3 \) emission and ~55% is attributed to animal livestock operations. Livestock barns are one of the major emission sources due to their large footprint. Therefore, a pressing need exists to develop effective emissions mitigation techniques. However, lack of reliable emission measuring techniques, especially for naturally ventilated (NV) livestock barns, impedes development of effective strategies for mitigating emissions. Furthermore, multiple inlets and outlets associated with NV animal housing and unstable ambient meteorology presents a huge challenge in the determination of ventilation rate.

Due to high investment in use of the direct method, indirect methods are preferably used for determining ventilation rates in NV animal buildings. In this thesis, two widely used indirect methods (\( \text{CO}_2 \)-balance and \( \text{H}_2\text{O} \)-balance method) were evaluated against a direct method. The results revealed that \( \text{CO}_2 \)-balance method overestimated barn air exchange rates (AER), while \( \text{H}_2\text{O} \)-balance method underestimated the AER. Integration time and wind velocity, on the other hand, had significant effects on both indirect methods. The two indirect methods also were not
reliable during milking time or at low indoor-outdoor differences in temperatures, absolute humidity, and CO₂ concentrations.

In view of complexity of current direct methods, two simple direct methods were developed and determined to be suitable for AER measurement with marginal relative errors. The two methods were based on measurements of wind speed at a local weather tower or at only one location adjacent to the center of the barn. The third simple approach, via CO₂-balance method, evaluated two gas-sampling regimes: indoor-outdoor and perimeter samplings. The results showed no significant differences between the two sampling regimes. The indoor-outdoor sampling regime was thus recommended because of its cost-effectiveness.

The last research component was the search for robust but simple and reliable devices for determining NH₃ concentrations in NV dairy barns. Towards this effort, two passive samplers, Ogawa passive sampler (Ogawa) and passive flux sampler (PFS), were evaluated against a photoacoustic infrared spectrooscope (INNOVA). Results indicated that the two passive samplers are reliable alternatives to the sophisticated and expensive INNOVA for up to three-days continuous monitoring of NH₃ concentrations in NV dairy barns.
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This dissertation is dedicated to my family, especially father, mother and my husband, who were always willing to support me in whatever way necessary.
1.1. Background

Concentrated animal feeding operations (CAFOs) have increasingly dominated livestock production in the United States and some other countries in the world (Dawson, 2010). The impacts of air contaminants from CAFOs on the environment and human health are serious threats to sustainability of the livestock industry. Emissions from CAFOs including odor, particulate matter, ammonia, hydrogen sulfide, volatile organic compounds, and greenhouse gases (Wang-Li et al., 2013), pose serious negative influences to animal welfare (Kaufman et al., 2015), human health, and sensitive ecosystems (Bittman et al., 2015), directly or indirectly, which have prompted stricter state and federal air quality regulations and legislations (Hristov et al., 2011). Factors influencing gas emissions from CAFO facilities include housing design, animal growing conditions, and operational and waste management practices (Wang-Li et al., 2013). However, limited emissions data from CAFOs impedes not only comprehensive assessment of their environmental impact but also development of effective strategies for mitigating emissions.

The challenge in measuring emissions from CAFOs is partly because pollutants originate from several sources, such as, animal housing, sand separator, manure storage facilities, and land application areas (Hristov et al., 2011). Naturally ventilated (NV) barns are a common animal housing type in warm and moderate climatic regions to conserve energy and to ensure productive and healthy animal environments (Andonov et al., 2003; Joo et al., 2014). The main weakness associated with NV systems is lack of precise control of ventilation rates compared to
mechanically ventilated systems, which have well-defined inlets and outlets. The standard measurement method of emission rate from mechanically ventilated animal housing is the product of ventilation rate and difference between gas concentrations at outlet and inlet points. However, multiple inlets and outlets of NV animal housing and unstable ambient meteorology conditions result in temporal variation of inlet and outlet positions (Calvet et al., 2013), which further complicates emissions determinations.

Developing a cost-effective technology and methodology to quantify gaseous emissions from livestock barns can provide more reliable gaseous emissions data for legislations, evaluations of potential abatement strategies of respective emissions, and validations of emissions models. This research focused on development of reliable as well as simple methods for measuring gaseous emissions from NV dairy barns.

1.1.1. Ammonia Emissions from Naturally Ventilated Dairy Buildings

Ammonia (NH₃), is an important alkaline gas in the atmosphere, which reacts with sulfates and nitrates to form secondary inorganic aerosols (Huang et al., 2012); contributing to ambient fine particulate matter that can impair atmospheric visibility and human health (Zhu et al., 2013). In addition, these fine particulates are eventually deposited onto soil or surface water bodies and may result in soil acidification in some soils or eutrophication in the surface waters (Huang et al., 2012). Emissions of NH₃, therefore, pose several serious environmental concerns including aerosol formation, soil acidification, and water eutrophication (Hristov et al., 2011).

In the U.S., over 80% of national NH₃ emissions are released from agricultural operations, and ~55% is attributed to animal livestock operations (Aneja et al., 2008; EPA, 2011). The major
sources of emissions in a typical dairy operation are the barns, the manure storages, and from field application of manure. The minor sources include the settling ponds, sand separation basins, solid-liquid operation units, and solids composting sites (Hristov et al., 2011). Wu (2012) also reported that the NV dairy barns constitute one of the largest NH₃ emission sources within agricultural production and contributed to more than 30% of total NH₃ emissions in Denmark. Therefore, it is important to measure NH₃ emissions, from dairy barns, in order not only to assess the contribution of emissions from these facilities but also to be able to develop and evaluate mitigation strategies and emission models.

Currently, however, there is no recognized reference method for measuring NH₃ emissions from NV dairy barns. As pointed out earlier, the two main parameters required for emission determination are the ventilation rate and gas concentration. Although the former parameter is the one with the greatest uncertainty in this process, the latter is faced with lack of reliable and cost-effective devices to measure gas concentrations. A good proportion of this dissertation presents several viable alternatives of determining ventilation rates and NH₃ concentrations in NV dairy barns.

1.1.2. Available Methods to Determine Ventilation Rates

Ventilation rate is the volume of air entering or leaving the building per unit time. Barn air exchange rate (AER), which is the number of times the barn fills with fresh air and empties dirty air, on the other hand, is quotient of ventilation rate and barn volume. In this thesis, the “ventilation rate” and “air exchange rate” were used interchangeably. Methods available for determining ventilation rates in animal buildings include direct methods and indirect methods, and direct methods are usually preferred because they are more accurate (Calvet et al., 2010). For
a mechanically ventilated livestock building with definite inlets and outlets, ventilation rate can
be monitored by Pitot tubes, hot wire anemometers, and fan wheel anemometers installed at the
ventilation ducts (Mosquera et al., 2012) or by recording the speed of the exhaust fan (Tremblay
et al., 2014). For a NV livestock building with numerous large openings, ventilation rate can be
monitored by ultrasonic anemometers or other velocity-measuring devices installed at the inlets,
outlets, or both (Flourentzou et al., 1998; Kiwan et al., 2012b). Local ventilation rate for a given
opening is the product of perpendicular velocity and opening area in question. The advantages of
the direct method are high frequency of simultaneous readings at numerous points and less
influences of measurements from animal physiology or behavior. The disadvantage is the
difficulty in obtaining a representative wind velocity for all the ventilation openings of a building
due to high variation in wind velocity at different positions of the ventilation openings (Ogink et
al., 2013). Increasing the number of the sensors overcomes this drawback but also increases the
cost. In a previous study (Joo et al., 2014), 16 ultrasonic anemometers were installed at select
points of the barn openings to measure air velocity at respective air inlets and outlets. The
research results showed that this increased reliability of the method but it tremendously increased
the measurement cost for practical applications since the total price of 16 ultrasonic
anemometers was ~$48,000 (a retail cost of ~$3000 for each) and similar increase in appropriate
hardware, operation, and maintenance costs.

Since the direct method for measuring ventilation rates in NV dairy barns requires a high
investment, indirect methods, which include the pressure difference method, tracer gas methods,
and mass balance methods, are widely used (Ogink et al., 2013). Each of these indirect methods
has its advantages, disadvantages, and appropriate application. The pressure difference method
determines pressure differences across all barn openings and computes airflow velocities from
these pressure differences according to Bernoulli’s theorem. This approach assumes that natural ventilation is primarily driven by the difference of wind pressure and of thermal buoyance. The natural ventilation method combines these two driving forces in an analytical model method and needs to be developed further since it is hard to predict wind pressure and thermal buoyance due to varying wind velocity and ambient microclimate (Kavolelis et al., 2008; Kiwan et al., 2012a). The tracer gas method comes in different variations including tracer gas decay, constant tracer concentration, and constant tracer injection rate. The major drawback of tracer gas technique is its major assumption of complete air mixing in the barn (Samer et al., 2011a; Samer et al., 2011b). Furthermore, the technique is limited to short durations of measurements and has indicated larger inconsistence compared to the CO₂-balance method (Samer et al., 2011a). The CO₂ mass balance method, equivalent to the constant tracer injection rate method discussed above, has showed good agreement with direct ventilation rate measurement in a modern manure belt laying hen house with a quasi-tunnel ventilation system (Li et al., 2005). Other studies further concluded that the CO₂-balance method can be used as an alternative or supplemental check for certain conditions where direct, continuous ventilation rate measurement is not feasible (Xin et al., 2009). The accuracy of this method, however, depends on CO₂ produced by the housed animals, which varies with animal weight, productivity, and pregnancy conditions. The H₂O-balance method is similar to the CO₂-balance method because it relies on water production mass balance to continuously determine the ventilation rate (Samer et al., 2012). The major sources of errors for both methods include the amount of CO₂ and H₂O produced by manure, variations in ambient temperature, locations of different measuring points and calculation models. Although the effects of these factors on these indirect methods are well recognized, their respective effects have not been adequately addressed in previous research. Furthermore, the
performance of one indirect method has often invariably been evaluated against another indirect method, which may also suffer from similar constraints.

Consequently, there is a need to evaluate these two widely used indirect methods (i.e., the CO₂-balance and H₂O-balance) against a direct method, and also to further develop the direct method to reduce the associated costs for practical purposes.

1.1.3. Available Methods to Determine Gas Concentrations

Credible measurements of gaseous concentrations from NV livestock barns are critical but still present considerable challenges. The success of air monitoring relies on sampling and analysis methods. The first challenge is choosing representative sampling positions, or a proper sampling strategy, to obtain a representative gas concentration, while the second challenge is selecting a reliable and affordable device for measurement of NH₃ concentration.

Lefcourt (2002) reported that incorrect selection of sampling positions may lead to gas concentration errors of over 200%. Research indicates that, to determine accurate emissions, air inlets-outlets of the buildings are the most reliable positions to measure gas concentrations (Demmers et al., 1998; Van Buggenhout et al., 2009; Ogink et al., 2013). However, for a NV livestock building, the openings can be both inlets and outlets, or change from inlet to outlet due to shifting wind patterns and local topography (Calvet et al., 2013), making selection of inlets and outlets difficult. Consequently, the common sampling strategy in NV buildings is indoor-outdoor sampling (Zhang et al., 2005; Ngwabie et al., 2009; Kiwan et al., 2013) instead of inlet-outlet sampling (also referred to as perimeter sampling in this thesis). In the direct method developed by Joo et al. (2014), perimeter sampling for one barn with five sampling lines requires at least five gas analyzers to obtain continuous measurements; while the indoor-outdoor
sampling for the same barn with three sampling lines require only two gas analyzers. At the current retail price of ~$50,000 for this photoacoustic IR Multigas Monitor (Model 1412, INNOVA AirTech Instruments, Ballerup, Denmark), five sets of these INNOVA monitors would require an upfront investment of ~$250,000 excluding the costs of sampling hardware, operation, and routine maintenance. These categories of instruments and sampling strategy, therefore, are rather elite making them impractical for routine monitoring of emissions in livestock barns.

A comprehensive review of available direct methods by Pedersen et al. (2004) for determining gaseous concentrations from NV animal buildings revealed a variety of devices ranging from ammonia sensors to infrared spectrophotometers, NO$_x$-analyzers, and multi-gas monitors. Zhang et al. (2005), Samer et al. (2011a), and Joo et al. (2014) measured gas concentrations using photoacoustic infrared spectroscopes to continuously analyze samples from selected points in the barn. Due to its high frequency measurements, this approach provides precise and reliable results, which also reveal the dynamics of gaseous emission. However, Rom and Zhang (2010) found that substantial time delays occurred to allow stabilization of gas, especially NH$_3$, when switching between high and low concentration positions, resulting in intermittent and not the intended continuous determination of gas concentrations. Furthermore, the cost of these equipment, maintenance, and labor are relatively high thus rendering them impractical for making measurements at more facilities, which is necessary for computation of reliable emission factors and evaluating mitigation strategies. Passive-sampling techniques present a viable inexpensive option for measuring NH$_3$ or other gases concentrations because they collect NH$_3$ or other gases without the need of a pump or other instruments requiring power supply thus rendering them easy to manufacture, transport and deploy. The passive samplers have been used to measure ambient sulfur dioxide, ozone, and ammonia concentration in Asia,
Africa, and South America (Carmichael et al., 2003). The results from these studies demonstrated that passive sampler offered low cost means of obtaining high quality measurement during long periods over large areas. However, only limited research on use of passive samplers in livestock barns has been conducted (Phillips et al., 1998; Losada et al., 2003; Cassel et al., 2005; Pereira et al., 2010). Another component of this dissertation, therefore, has been dedicated to research alternative cost-effective but reliable methods for measuring NH₃ concentrations in NV dairy barns.

1.2. Research Objectives

The preceding introduction has highlighted the importance of ventilation rates and gas concentration determinations in determining credible emissions in NV dairy barns. Thus, the overall goal of this research was to develop robust, simple or practical direct and indirect, reliable and cost-effective methods for quantification of gaseous emission from NV dairy barns. The following specific objectives were pursued to achieve this overall goal:

1. Evaluate two frequently used indirect methods including the CO₂-balance method and the H₂O-balance method against a direct AER measurement method for NV dairy barns;

2. Develop potential simple approaches for determining AER via direct measurement of airflow rate to derive AER or indirect measurements of AER using CO₂-balance method in NV dairy houses; and

3. Assess the potential use of passive samplers as alternative cost-effective approaches for measurements of NH₃ (and other gases) concentrations in NV dairy barns.
1.3. Dissertation Structure

The goal of this thesis was to develop or evaluate robust, simple, direct or indirect, reliable, and cost-effective methods for determining ventilation rates and concentrations in NV dairy barns. Each of the following three chapters addresses one of the three specific objectives outlined in the “Research objectives” section above. Chapter Two evaluates determination of AER or ventilation rates of NV dairy barns via two commonly used indirect methods against a direct method. Three potential simple approaches for determining AER in NV dairy barns are presented in Chapter Three. Chapter Four presents two passive samplers as alternative devices for measuring NH₃ concentrations in NV dairy barns. Finally, Chapter Five summarizes the major conclusions and inferences drawn from the entire thesis and also offers suggestions for future work.
1.4. References


Xin, H., Li, H., Gates, R.S., Overhults, D.G., Earnest Jr, J.W., 2009. Use of CO$_2$ concentration difference or CO$_2$ balance to assess ventilation rate of broiler houses.

CHAPTER TWO
DIRECT VERSUS INDIRECT METHODS FOR MEASURING VENTILATION RATES
IN NATURALLY VENTILATED DAIRY HOUSES

2.1. Abstract
Indirect methods are widely used for determining air exchange rates (AER) in naturally ventilated buildings because they are relatively easier and less expensive than direct methods. The main goal of this study was to evaluate two common indirect methods (CO$_2$ and H$_2$O mass balances) against a direct method, and identify factors influencing these indirect methods. Indirect methods with 24-h data averaging yielded more reliable AER than with shorter averaging times (i.e., 1, 2, and 12 h). The mean AER based on 24-h averaging ranged from 11 to 39 h$^{-1}$ across all study periods and methods. The CO$_2$-balance method tended to overestimate AER, while the H$_2$O-balance method tended to underestimate AER. The cows’ CO$_2$ production rate was estimated at 0.178 m$^3$ h$^{-1}$ hpu$^{-1}$, the correction factor $K_s$ was estimated at 0.65, based on 24-h data averaging for our study barn. Barn AER increased with wind speeds. For specific wind directions, barn AER was not significantly different amongst the three methods. However, wind directions significantly affected barn AER regardless of the method. The differences between CO$_2$-balance and direct method varied significantly across wind directions. Indirect methods were unreliable during milking times, and when indoor-outdoor temperature, absolute humidity, and CO$_2$ concentration differences were less than 1.0°C, 0.3 g m$^{-3}$ and 100 ppm, respectively.

**Key words:** Emission; water vapor balance; carbon dioxide balance; air exchange rate; environment
2.2. Introduction

Accurate and reliable measurements of gaseous emissions in animal husbandry are critical for development and evaluation of mitigation strategies and compilation of national emission inventories. Quantifying gas emissions from naturally ventilated barns, however, has additional challenges primarily because of the complexity of air exchange rates (AER) determination (Kiwan et al., 2012; Ogink et al., 2013). Natural ventilation (NV) systems in dairy barns are commonly used in regions with mild climate due to lower investment costs and low energy demand (Andonov et al., 2003; Samer et al., 2011; Joo et al., 2014). However, AER in NV barns are directly dependent upon atmospheric conditions (Snell et al., 2003; Ngwabie et al., 2011). Uncertainties due to changes in meteorological conditions, therefore, further complicate estimation of AER in NV buildings.

Air exchange rates in NV buildings can be measured directly by determining airflow velocities in and out of the building (hence: direct method), which is the fundamental approach. Wind velocities at the openings are then coupled with corresponding openings’ areas to determine ventilation rate or AER. The advantages of this direct approach, over indirect methods, include: (i) high frequency of simultaneous readings at numerous points, and (ii) less influences of measurements from animal physiology or behavior. Direct measurements of AER in the field, however, are few due to substantial initial investment required (Flourentzou et al., 1998; Kiwan et al., 2012; Joo et al., 2014). The accuracy of the direct method mainly depends on the number of measurement points because wind velocity sensors can measure only local wind velocities while wind velocities at different positions of the ventilation openings may vary significantly (Ozcan et al., 2007). Increasing the number of the sensors overcomes this drawback but also increases the cost. In a previous study (Joo et al., 2014), 16 ultrasonic anemometers (sonics)
were installed at select points of the barn openings to measure air velocity at respective air inlets and outlets. This research concluded that the sum of airflow rates through all openings acting as inlets was the best measure of barn ventilation rate for that given period.

The AER from NV buildings are also measured using indirect methods such as tracer gas techniques (TGT) and mass balance methods (CO$_2$-balance, H$_2$O-balance, and heat balance). The major assumption in the TGT is complete air-mixing, but this condition is rarely achieved in NV buildings (Samer et al., 2011). Furthermore, TGT is limited to short durations of measurements when using sulfur hexafluoride (SF$_6$) or radioactive isotope Krypton85 ($^{85}$Kr) as tracer gases and has indicated larger inconsistences compared to the CO$_2$-balance method, which is another form of tracer gas application (Samer et al., 2011). The CO$_2$-balance method, based on CO$_2$ production by animals, is one of the most commonly used methods in NV buildings (CIGR, 1984, 2002). Research indicated that the CO$_2$-balance method agreed well with the direct method (Xin et al., 2009). Another commonly used indirect method is the H$_2$O-balance, which relies on animals’ water production and water mass balances between air inside and outside buildings (Pedersen et al., 1998; Chepete and Xin, 2004; Blanes and Pedersen, 2005; Samer et al., 2012a; Samer et al., 2012b). The heat balance method, which is based on heat production rate of animals, is not recommended for uninsulated buildings due to high potential errors when estimating heat transmission loss from such buildings (Pedersen et al., 1998). The accuracy of these indirect methods, however, depends on CO$_2$, H$_2$O, and heat produced by the housed livestock, which varies with animal weight, productivity, and pregnancy conditions. Major sources of errors also include unaccounted CO$_2$ and H$_2$O produced from manure, variations in meteorological conditions, locations of sampling points, and inadequacy of calculation models. Although the effects of these factors on these indirect methods are well recognized, their respective effects
have not been adequately addressed in previous research. Furthermore, performance of one indirect method has often invariably been evaluated against another indirect method, which may also suffer from similar constraints.

The specific objectives of this study, therefore, were to: (i) evaluate the performances of two select indirect methods (CO$_2$ and H$_2$O mass balances) against the direct method in NV dairy barns, and (ii) investigate the effects of pertinent factors (integration time, wind velocity, temperature, humidity, CO$_2$ concentration and milking time) on these two indirect methods.

2.3. Materials and Methods

2.3.1. Dairy Site and Building Description

These studies were conducted in a NV dairy barn on a commercial dairy operation located in central Washington. The dairy consisted of six symmetrically distributed freestall NV dairy buildings and other dairy amenities including: milking parlor, feed storage and mixing, and manure storages and treatment facilities (Fig. 2.1). Barn 2, which had a capacity for 850 Holstein cows, was selected for studies reported in this paper. An on farm instrument shelter (OFIS) was located between barns 1 and 2.

The study barn (B2) was 213 m long and 39 m wide and was partitioned into two equal pens by a concrete pad feed alley (Fig. 2.2). The height of roof varied from 3.6 m at the sidewalls to 11.0 m at the gable peak. The barn had an open ridge (1.85 m wide) and space boards covering the gables of the east and west endwalls. Each of the longer south and north sidewalls of B2 had two side-by-side adjustable side curtains to allow control of natural ventilation. Usually one or both curtains were closed from November to March because of the prevalent windy and cold
conditions. When both curtains were closed, there was still a 40-cm opening between the top curtain and the eave.

Figure 2.1 An aerial view of the research site and study barn (B2) (Joo et al., 2014).
2.3.2. Instrument Setup and Data Acquisition

Wind velocities, perpendicular to barn openings, were continuously measured with 16 three-dimensional (3-D) sonics (Model 81000, R.M. Young Co., Traverse City, MI) as shown in Fig. 2.3. Twelve sonics were distributed amongst the four sidewalls, while four units were mounted at the open ridge of the barn. The barn was divided lengthwise into four equal virtual sections. The sidewall sonics were mounted at approximately the midpoint of each section with the sensors positioned in the middle of the opening between the eave and the top edge of upper curtain. The four sonics in the ridge opening were mounted horizontally at the midpoint of each...
section. Each endwall was divided evenly into two virtual sections. The two sonics in each endwall were installed at the horizontal and vertical midpoints of each section.

![Diagram of barn layout](image)

Figure 2.3 Layout of the barns, on-farm instrument shelter (OFIS), and monitoring locations: (a) end view; (b) plan view; (c) side view (none of the views is drawn to scale).

Carbon dioxide concentrations were measured using a photoacoustic IR multigas monitor (Model 1412, Innova AirTech Instruments, Ballerup, Denmark). Sixteen sampling ports were co-located adjacent to each sonic around the barn perimeter. Each sampling port was provided with an air filter. The four sampling ports at each sidewall or on the ridge were combined into one
composite sample line, while the two sampling ports on each endwall were pooled together to yield a composite sample line for each endwall. In effect, the sampling lines summed up to ten: five for barn 1 and five for barn 2 (B1 was also monitored during the study period but its data are not included in this paper). Samples from all sampling lines for concentration measurements were drawn sequentially at intervals of 10 min and it thus took 100 min to complete a sampling cycle. Collection, conveyance, and analyses of gas were described in detailed in Joo et al. (2014) and Joo et al. (2015).

The ambient meteorological conditions were measured with a weather station installed middle of B1 ridge. The weather station consisted of a solar radiation shielded relative humidity (RH)-temperature probe (NOVUS Model RHT-WM, Novus Electronics, Porto Alegre, Brazil), a solar radiation pyranometer (Model LI-200SL, LiCOR, Lincoln, NE) and a wind anemometer (Model 03002VM Wind Sentry, R.M. Young Co., Traverse City, MI). The air temperature and relative humidity inside the barn were recorded using a RH-temperature probe (NOVUS Model RHT-WM, Novus Electronics, Porto Alegre, Brazil) located near the middle of the barn at a height of approximately 8 m. The sonics also provided additional temperature measurements besides the air velocity measurements.

The measurement data were collected using a DAC (data acquisition and control) hardware and an AirDAC (air emissions data acquisition and control) software custom-developed by Purdue University and National Instrument which control the sampling duration, sequence, and frequency of gas sampling lines (Ni and Heber, 2010; Joo et al., 2014; Joo et al., 2015).
2.3.3. Theory and Methods

2.3.3.1 Direct Method

The direct method applies the fluid continuity equation (Eq. 2.1) to compute barn ventilation rates (Joo et al., 2014) and Eq. (2.2) to determine AER.

\[ Q = 3600 \nu A \]  
\[ AER_{Direct} = \frac{Q}{V} \]

Where: \( Q \) is airflow through the opening (m\(^3\) h\(^{-1}\)), \( \nu \) is the average perpendicular air velocity to the face of the opening (m s\(^{-1}\)), \( A \) is the opening area (m\(^2\)), for a given barn inlet or outlet; \( AER_{Direct} \) is air exchange rate by direct method (h\(^{-1}\)), and \( V \) is the barn volume (m\(^3\)). Each of the five barn openings (four walls plus the ridge), at any given period, was either an inlet or outlet depending on the prevailing wind directions. Total air inflow rates were used to represent ventilation rates (Joo et al. 2014).

2.3.3.2 H\(_2\)O-Balance Method

The H\(_2\)O increase in the air exiting livestock building, which originates from respiration of animals, evaporation of spilt water, wet feed, and manure, is the basis of AER determination using the H\(_2\)O-balance method. The latent heat required for water evaporation comes from the animals’ sensible heat production. Total, sensible, and latent heats are calculated using Eq. (2.3) to (2.8) (CIGR, 1984, 2002; Blanes and Pedersen, 2005).

\[ \phi_{tot} = \phi_{LM} + \phi_{MY} + \phi_d = 5.6m^{0.75} + 22Y + 1.6 \times 10^{-5}d^3 \]  

Where: \( \phi_{tot} \) is total heat production by the animals at 20°C (W); \( \phi_{LM} \) is heat dissipation due to maintenance of essential function (W); \( \phi_{MY} \) is heat dissipation due to milk yield (W); \( \phi_d \) is heat dissipation due to pregnancy (W); \( m \) is body mass of the cow (kg cow\(^{-1}\)); \( Y \) is milk yield (kg cow\(^{-1}\)) and \( d \) is the diameter of the barn (m).
cow$^{-1}$ d$^{-1}$); $d$ is days of pregnancy (d). Because of the challenge of obtaining information on the pregnancy days of individual cows during measurements, heat dissipation due to pregnancy is usually ignored in Eq. (2.3) (Wang et al., 2006; Ngwabie et al., 2011; Samer et al., 2012a). Total heat production for temperatures other than 20°C ($\phi^*_\text{tot}$) is corrected for temperature as shown in Eq. (2.4). Correspondingly, the sensible heat ($\phi^*_\text{sen}$) and latent heat ($\phi^*_\text{lat}$) are presented in Eq. (2.5) and (2.6) respectively. Since a proportion of total heat production is used to evaporate water from the feces, urine and feed, the sensible heat losses are reduced by the correction factor $K_s$ (0.85) for a dairy barn practicing dry feeding and maintaining average floor conditions (CIGR, 1984; Pedersen et al., 1998). The corrected sensible heats ($S$) and latent heats ($L$) are given in Eq. (2.7) and (2.8), whereas Eq. (2.9) presents the barn AER in terms of latent heat consumed to increase humidity of the air exiting the barn.

\[
\phi^*_\text{tot} = \phi_{\text{tot}}(1 + 0.004(20 - T_{\text{ind}})) \quad (2.4)
\]

\[
\phi^*_\text{sen} = 0.71\phi^*_\text{tot} - 0.408 \times T_{\text{ind}}^2 \quad (2.5)
\]

\[
\phi^*_\text{lat} = \phi^*_\text{tot} - \phi^*_\text{sen} \quad (2.6)
\]

\[
S = K_s\phi^*_\text{sen} \quad (2.7)
\]

\[
L = \phi^*_\text{tot} - S \quad (2.8)
\]

\[
AER_{H_2O} = \frac{3600L}{h_{\text{vap}}(H_{\text{ind}} - H_{\text{out}})V} \quad (2.9)
\]

\[
h_{\text{vap}} = (2501 - 2.42T_{\text{ind}}) \times 10^3 \quad (2.10)
\]

Where: $AER_{H_2O}$ is the air exchange rate by H$_2$O-balance method (h$^{-1}$); $H_{\text{ind}}$ and $H_{\text{out}}$ are the moisture content of the indoor and outdoor air (kg [H$_2$O] m$^{-3}$ [air]); $h_{\text{vap}}$ is the heat of vaporization of water (J kg$^{-1}$); $V$ is the barn volume; $T_{\text{ind}}$ is the indoor temperature (°C).
Determination of moisture contents from relative humidity and temperature are presented in Chepete and Xin (2004) and ASHRAE (2001).

2.3.3.3 CO₂-Balance Method

Barn AER by CO₂-balance method was computed as the quotient of the CO₂ production rate (Eq. 2.11) and the difference between the CO₂ concentration at the outlets and the inlets (Eq. 2.12). In general, most of CO₂ in NV barn is from respiration of the housed animals. The manure (urine and feces), however, also produces some CO₂ but this amount is usually less than 5% of the amount produced via animal respiration and is thus usually neglected in the mass balance model. Computations using Eq. (2.11) and (2.12) assume ideal air-mixing inside the barn (Pedersen et al., 1998; CIGR, 2002; Blanes and Pedersen, 2005; Zhang et al., 2005):

\[
C_{\text{prod}} = 0.185 \phi^*_{\text{tot}} / 1000 \quad (2.11)
\]

\[
AER_{CO_2} = \frac{C_{\text{prod}}}{10^{-6}(C_{\text{out}} - C_{\text{in}})} \quad (2.12)
\]

Where: \(C_{\text{prod}}\) is the CO₂ production (m³ h⁻¹) on a 24-h basis; 0.185 is a fixed CO₂ production rate (0.185 m³ h⁻¹ HPU⁻¹); one heat production unit (HPU) is 1000 W of the total heat produced by the animal at 20°C; \(AER_{CO2}\) is the air exchange rate by CO₂-balance method (h⁻¹); \(C_{\text{in}}\) and \(C_{\text{out}}\) are the CO₂ concentrations (ppm) in the inlet and outlet air, respectively.

2.3.4. Data Processing and Analysis

The direct method was considered as the reference method in all the analyses in this paper. Barn AER values lying outside of 1.5 IQR (interquartile range), during respective study periods, were designated outliers and were not used in subsequent analyses (Sancho et al., 2014;
Joo et al., 2015). The lowest percentages of respective usable data compared to total data collected (i.e., 1-h averaging data processing) were 98% for direct method, 88% for CO₂-balance, and 82% for H₂O-balance method. To determine the effect of temperature difference between indoor and outdoor, data were first sorted with respect to temperature difference, from lowest to highest. The mean AER within 0.5°C intervals were then computed to reduce data points to a reasonable number for regression analyses as well as for figure plotting purposes. In order to evaluate the effect of wind direction, Data were classified into eight specific wind directions (N, NE, E, SE, S, SW, W, and NW). The statistical analyses were conducted using SAS v9.2 software package (SAS Institute, Cary, NC, USA). ANOVA, paired t-tests and Tukey’s pairwise comparison tests were conducted to determine effects of wind direction and method on barn AER at α = 0.05 significant level.

2.4. Results and Discussion

2.4.1. Measurement Periods, Barn, and Weather Information

The analyses in this paper were based on four different sets of data samples representing all four seasons in a year. These data sets were selected based on the most stable operation periods during each measurement campaign (i.e., no instrumentation, technical or other management problems). Details of the data collection periods and pertinent weather conditions are shown in Table 2.1. The study barn housed approximately 850 Holstein cows during the entire measurement campaign period. The average weight for each cow was about 675 kg, while the average milk production was 30 kg d⁻¹ cow⁻¹.
Table 2.1 Data collection periods and environmental conditions

<table>
<thead>
<tr>
<th>Seasons</th>
<th>Month</th>
<th>Wind speed (m s$^{-1}$)</th>
<th>Temperature (°C)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Indoors</td>
<td>Outdoors</td>
</tr>
<tr>
<td>Winter</td>
<td>March</td>
<td>3.3±3.3</td>
<td>9.9±4.0</td>
<td>6.7±3.7</td>
</tr>
<tr>
<td>Spring</td>
<td>May</td>
<td>3.8±3.6</td>
<td>15.5±3.3</td>
<td>14.2±3.8</td>
</tr>
<tr>
<td>Summer</td>
<td>July</td>
<td>2.3±1.9</td>
<td>27.6±6.1</td>
<td>27.1±6.6</td>
</tr>
<tr>
<td>Autumn</td>
<td>September</td>
<td>1.5±1.4</td>
<td>23.7±8.2</td>
<td>20.9±6.1</td>
</tr>
</tbody>
</table>

Temperature and wind speed not only varied across seasons but also fluctuated widely (manifested in large standard deviations) during one contiguous measurement period probably because of large variations in these parameters during daytime and nighttime and from day to day variations within these 7-d measurement periods. The mean differences between average indoor and outdoor temperatures ranged from 0.5°C in summer to 3.2°C in winter; suggesting that fully open sidewall curtains during summer improved ventilation, allowing indoor temperature to approach the outdoor temperature. The fully closed curtains during winter, however, limited barn ventilation and thus kept indoor temperatures significantly above outdoor temperatures. Although the average wind speed was higher in winter than in summer, the fully closed curtains were effective in limiting AER. Fig. 2.4 represents local average wind speeds and directions during the respective measurement periods. The prevailing wind directions were southwest in March (winter) and May (spring), while the prevailing wind directions were northwest in July (summer), and north or southwest in September (autumn).
2.4.2. Seasonal Variations of AER

Air exchange rates during the four measurement periods, for each of the three measurement methods, are shown in Fig. 2.5. The AER varied significantly with season but were generally lower during cool seasons (March and September) and higher during warm seasons (May and July). The mean AER, based on 24-hour averaging, ranged between 11 and 39 h$^{-1}$ for all study periods and across all three methods. The standard minimum AER, in order to provide a safe and healthy environment (with respect to moisture, temperature, dust, pathogens, and gaseous contaminants levels) in mechanically ventilated dairy barns, ranged from 4 h$^{-1}$ in winter to 60 h$^{-1}$ in summer (Bates and Anderson, 1979; Heber, 1990; Gooch, 2008). The AER for our
NV study barn, therefore, always exceeded the standard minimum dairy barn ventilation requirements.

Figure 2.5 Air exchange rates (AER) by the three methods based on 24-h data averaging (solids dots represent means; lines dividing the boxes show medians; the top and bottom of box plots indicate first quartiles (Q1) and third quartiles (Q3), respectively; while the upper and under whiskers indicate the maximum and minimum values within 1.5 times the interquartile range, respectively).

Alternatively, Fig. 2.6 represents the differences between the indirect methods and direct method over the four seasons based on the 24-h and 1-h data averaging. The CO2-balance method, in general, resulted in the highest AER values amongst the three methods, while the H2O-balance method resulted in the lowest values (Fig. 2.6a). Potential sources of errors for the indirect methods are assumptions made in the calculation models (inaccuracies of the cow’s CO2 production rate and partitioning of sensible and latent heats), and an unaccounted amount of CO2
and H₂O released from manure. In previous research, Blanes and Pedersen (2005) stipulated that only 83% to 90% of the AER are explained by the balance models. The AER by H₂O-balance method were closest to that by the direct method in March. During March, all curtains were closed, therefore, the ventilation system resembled that of a MV barn, and the H₂O-balance method is thus relatively more reliable for AER estimation in MV buildings (Pedersen et al., 1998; Samer et al., 2012a).

Figure 2.6 The differences in air exchange rates (ΔAER) by CO₂-balance and H₂O-balance methods using the 24-h and 1-h averaging processes (solids dots represent means; lines dividing
the boxes show medians; the top and bottom of box plots indicate first quartiles (Q1) and third quartiles (Q3), respectively; the upper and under whiskers indicate the maximum and minimum values within 1.5 times the interquartile range; and the open dots represent outliers).

The AER obtained by both the 24-h averaging and the 1-h averaging show similar seasonal trends (Fig. 2.6b). However, the 1-h averaging produced significantly many outliers, while the 24-h averaging produced no outliers. These results are a reflection of the wide range of diurnal variations in the production of H₂O and CO₂. The 1-h averaging also indicated wider distribution or scatter of AER compared to the 24-h averaging. In absolute terms, however, the 1-h averaging, for the H₂O balance, resulted in more reliable AER than the 24-h averaging with respect to the direct method. The converse was true with the CO₂-balance method, which indicated that AER was closer to those of direct method with the 24-h averaging, compared to the hourly averaging. Although the 24-h averaged AER are more dependable for determining cumulative emissions, with the CO₂ balance, it is not possible to utilize these data to map diurnal variations of emission rates since pollutant emissions and AER change widely in both time and space. Barn AER computed by either the 1-h or the 24-h averaging processes, for either the H₂O or the CO₂ mass balances, needs to be interpreted cautiously because of these inherent limitations. Overall, these results suggest that for situations where diurnal variations need to be captured, the H₂O balance is more appropriate than the CO₂ balance but when the desired output is cumulative daily emissions, the latter is more suitable than the former.
2.4.3. Effect of Other Integration Times

Indirect methods are impacted by factors that change with both time and space. Fig. 2.7 shows the effect of four different integration times of data processing on the performances of the indirect methods. The correlation coefficient between the indirect methods and the direct method increased with integration time. The corresponding p-value of the paired t-test between AER by the CO₂-balance method and direct method were <0.0001, <0.0001, 0.0082, and 0.1510, at integration times of 1, 2, 12, and 24 h, respectively. The results further show that the barn AER yielded by the CO₂-balance method based on 24-h average were not significantly different from those obtained by the direct method (p > 0.05). This phenomenon is partly consistent with that reported in a previous study (Li et al., 2005), which showed non-significant differences in AER between the CO₂-balance method and direct method for MV broiler houses with integrating times above 2 h. Although the 24-h averaging was more reliable for the CO₂-balance method, it did not account for temporal variations. For the H₂O-balance method, integration times of 1 h and 2 h resulted in AER that were not significantly different from the direct method (p > 0.05). The corresponding p-values of the paired t-test between AER by the H₂O-balance method and direct method were 0.115, 0.1246, 0.0089, and 0.0005, at integration times of 1, 2, 12, and 24 h, respectively. The significant underestimations by H₂O-balance method based on 12 and 24-h averaging were attributed to H₂O-balance model’s (see equations 2.4, 2.5, and 2.10) inadequacy in capturing diurnal variations. The AER by the CO₂-balance were higher than the direct method values, while the H₂O-balance method values tended to be less than or close to direct method values. The higher AER by the CO₂-balance may be attributed to the applicable CO₂ production model (Eq. 2.11). The CO₂ production rate value of 0.185 m³ h⁻¹ hpu⁻¹ may be responsible for observed overestimations of AER. The CO₂ production rate needed to be adjusted to 0.178 m³
h^{-1} hpu^{-1} for our study barn for the CO₂-balance to yield AER comparable to the direct method, which was in the 0.17 to 0.20 m³ h^{-1} hpu^{-1} range reported in a previous study (Van Ouwerkerk and Pedersen, 1994).

Figure 2.7 Effect of integration time on computation of AER using indirect methods.

The underestimation of AER by the H₂O-balance may be attributed partially to inadequate partitioning of latent and sensible heats in the heat production model (Eq. 2.7). The correction factor $K_s$ (0.85) applied to sensible heat may be larger than actual correction factor value, which led to underestimation of the evaporative latent heat due to water from feces, urine
and feed in the study barn. In this study, the $K_s$ needed to be adjusted to 0.65 for the H$_2$O-balance to yield identical AER as that by direct method. The $K_s$ of 0.65, however, fell outside of the 0.8 to 1 range reported by Pedersen et al. (1998). Although higher the integration times seemed more reliable than shorter time, the 1-h averaging is superior for determining temporal or diurnal variations of AER. Consequently, 1-h data averaging was chosen to analyze the effects of other pertinent factors on the performances of indirect methods in the next section.

2.4.4. Effect of Wind Speed and Direction
2.4.4.1. Wind Speed

Local wind speeds during the four seasons fluctuated widely, ranging from 0.09 to 17.40 m s$^{-1}$ although 88% of wind speeds were below 6 m s$^{-1}$. Fig. 2.8a presents the variation of AER with wind speeds for each of the three methods under northeasterly winds (22.5°–67.5°). Barn AER increased with wind speeds (coefficient of determination $R^2$ were 0.79, 0.53, and 0.24 for the direct, CO$_2$-balance, and H$_2$O-balance methods, respectively). This observation is consistent with ventilation theorem and other empirical data (Wu et al., 2012). These results also reveal that AER were explained better by wind speed in the direct method than in the indirect methods. Fig 2.8b, on the other hand, shows that an increase in wind speed had limited influence on the differences in AER between the indirect and direct methods ($R^2 = 0.11$ and 0.13 for CO$_2$-balance and H$_2$O-balance, respectively). One possible reason for this is that increased wind speed resulted in higher evaporation of extraneous water from manure, bedding, and feeds, and higher volatilization of CO$_2$ from manure, which further distorted the H$_2$O or CO$_2$ productions by the animals in the respective models.
Figure 2.8 (a) Relationships between AER and wind speed for northeasterly winds (22.5°–67.5°), and (b) differences in AER (ΔAER) between indirect methods and direct method at the same wind condition.

Generally, high wind speeds are expected to enhance barn AER. As a result, the temperature differences between inside and outside the barn, therefore, should decrease concurrently with an increase in wind speeds. These stipulations are strongly (R² = 0.78) supported by the analyses presented in Fig. 2.9. Although temperature differences provide buoyant force that induces air exchange in livestock buildings, wind speed is evidently the
primary factor governing AER as compared with temperature difference, perhaps, because of its
direct influence on air exchange within the barn (Barrington et al., 1994; Zhang et al., 2005;
Norton et al., 2009).

![Graph showing variation of temperature difference (ΔT) between indoor and outdoor air with wind speed.](image)

Figure 2.9 Variation of temperature difference (ΔT) between indoor and outdoor air with wind speed.

2.4.4.2. Wind Direction

The relationships between AER determined by each of the three methods and wind
directions as well as relationship between wind speeds and wind directions are both presented in
Fig. 2.10. The barn AER was strongly dependent on wind directions regardless of methods
adopted. The mean barn AER by direct method for northerly winds (34.8 h⁻¹ at the mean wind
speeds of 1.26 m s⁻¹), for instance, was 1.62 times greater than for westerly winds (21.5 h⁻¹ at
the mean wind speeds of 4.60 m s⁻¹). This result can be explained by the wind incident angle (De
Paepe et al., 2013). The wind was normal or perpendicular to the long north-wall of the barn, for
northerly winds; while for westerly winds, the west end-wall receiving the wind was shorter, resulting in less airflow into the building. This result explains why orientation of NV buildings must always take into account prevailing wind direction to optimize natural ventilation.

Figure 2.10 a) Relationships between AER determined by three methods and wind directions and also b) relationships between wind speeds and wind directions.
The mean wind speeds, the mean AER by the three methods, and the mean AER differences between indirect and direct methods under eight wind directions are presented in Table 2.2.

Table 2.2 Means (±standard deviations) of wind speeds and AER determined by the three methods at eight specific ranges of wind directions.

<table>
<thead>
<tr>
<th>Wind direction (degree)</th>
<th>Data points</th>
<th>Wind speed m s⁻¹</th>
<th>Direct</th>
<th>CO₂</th>
<th>H₂O</th>
<th>Difference between indirect methods and direct method</th>
</tr>
</thead>
<tbody>
<tr>
<td>N (337.5–322.5)</td>
<td>93</td>
<td>1.25±0.84</td>
<td>ab</td>
<td>34.8±14.9 A</td>
<td>ab</td>
<td>63±12.0</td>
</tr>
<tr>
<td>NE (22.5–67.5)</td>
<td>69</td>
<td>1.73±1.35</td>
<td>a</td>
<td>34.3±19.7 A</td>
<td>ab</td>
<td>325±15.8 A</td>
</tr>
<tr>
<td>E (67.5–121.5)</td>
<td>51</td>
<td>1.23±1.18</td>
<td>c</td>
<td>19.8±13.5 A</td>
<td>b</td>
<td>17.9±12.4 A</td>
</tr>
<tr>
<td>SE (112.5–157.5)</td>
<td>56</td>
<td>2.66±2.70</td>
<td>bc</td>
<td>24.9±16.5 A</td>
<td>b</td>
<td>19.4±13.5 A</td>
</tr>
<tr>
<td>S (157.5–202.5)</td>
<td>58</td>
<td>2.97±2.48</td>
<td>bc</td>
<td>24.5±16.0 B</td>
<td>b</td>
<td>20.9±10.6 B</td>
</tr>
<tr>
<td>SW (202.5–247.5)</td>
<td>124</td>
<td>3.30±3.36</td>
<td>ab</td>
<td>25.4±15.7 B</td>
<td>b</td>
<td>23.4±11.9 B</td>
</tr>
<tr>
<td>W (247.5–292.5)</td>
<td>128</td>
<td>4.60±3.63</td>
<td>c</td>
<td>21.5±12.8 B</td>
<td>ab</td>
<td>9.7±12.9</td>
</tr>
<tr>
<td>NW (292.5–337.5)</td>
<td>92</td>
<td>2.36±2.21</td>
<td>ab</td>
<td>32.0±16.5 A</td>
<td>a</td>
<td>12.3±15.4</td>
</tr>
</tbody>
</table>

* Means with different upper case letters in the same row (i.e. for a specific wind direction) or means with different lower case letters in the same column (i.e. for a specific wind direction) indicate significant differences at α=0.05.

The ANOVA indicated a significant interaction between the methods and wind directions (p = 0.020). Paired t-tests indicated that the methods had no significant effect on the AER at a given wind direction besides the inherent characteristics of overestimation by CO₂-balance and underestimation by the H₂O-balance method. For each method, however, Tukey’s pairwise comparison test showed that wind directions had a significant effect on AER. The mean barn AER from the three methods were lower for easterly winds and westerly winds due to smaller open areas receiving wind. The barn AER from northerly winds (NW, N, NE) was significantly
higher than from southerly winds (SW, S, SE), which was attributed to more windbreaks or obstacles to the barn’s south partially sheltering the south wall. Furthermore, for each method, wind directions had a significant effect on the differences between the CO$_2$-balance method and direct method, and no significant effect on the differences between the H$_2$O-balance method and direct method. The differences between the CO$_2$-balance method and direct method for northwesterly winds (NW, W, N) were significant higher than for other winds, especially easterly winds (SE, E, NE). These differences may be attributed to incomplete mixing due to high northwesterly wind speeds.

2.4.5. Effect of Temperature, Humidity and CO$_2$ Concentration

The effects of temperature, absolute humidity and CO$_2$ concentration differences on barn AER by the indirect methods are presented in Fig. 2.11. The differences between indoor and outdoor temperatures varied with seasons. Indoor temperatures were usually higher than outdoor temperatures. Lower indoor temperatures were rare and often occurred during warm periods (July and May). Indoor and outdoor temperature differences, in general, were larger than 2.5°C during cool periods (March and September) indicating lower barn AER. The AER differences between the CO$_2$-balance method and direct method were greater at lower temperature differences (below 1°C) than at higher temperature differences (Fig. 2.11a).

The absolute humidity of indoor air is usually higher than that of outdoor air due to respiration from cows, evaporation of spilt water, wet feed, and manure, except during precipitation. Mean hourly absolute humidity data evidently revealed this general trend. The AER differences between H$_2$O-balance method and direct method relative to absolute humidity difference presented in Fig. 2.11b shows the same pattern as that relative to temperature
differences (Fig. 2.11a). The differences between the H₂O-balance method and direct method were higher below absolute humidity difference of 0.3 g H₂O m⁻³, and significantly different if outdoor absolute humidity was close to or higher than indoor absolute humidity.
Except during 6% of milking time, the CO\textsubscript{2} concentration of indoor air was usually higher than that of outdoor air due to respiration from cows and decomposition from manure. The AER differences relative to CO\textsubscript{2} concentration difference presented in Fig. 2.11c shows the differences between the CO\textsubscript{2}-balance method and direct method were higher when CO\textsubscript{2} concentration difference was less than 100 ppm.

These results agree with those reported in previous studies. Pedersen et al. (1998) concluded that the CO\textsubscript{2}-balance and H\textsubscript{2}O-balance methods were unreliable when small differences occurred between inside-outside: temperatures (less than 2 °C), absolute humidity (less than 0.5 g water m\textsuperscript{-3} air), or CO\textsubscript{2} concentration (less than 200 ppm). These researchers noted that random variations between AER estimated respectively by the CO\textsubscript{2} and H\textsubscript{2}O balance...
equations were greater at these low temperatures, humidity and concentration differences regimes. In general, conditions of excellent ventilation for NV animal housing result in smaller or narrower temperature, humidity and concentration differences between inside and outside the barn, which may result in relatively larger errors. The results suggest that indirect methods are more reliable in estimating AER for poorly ventilated NV dairy barns (i.e. during periods of poor ventilation) or for controlled ventilation systems found in mechanically ventilated dairy barns.

2.4.6. Effect of Milking Time on Indirect Methods

The cows in the study barn were milked twice a day starting at approximately 4:00 am and 4:00 pm. In each session, all cows in one of the two pens were moved out to the milking parlor and returned to their respective pens in one hour. In the second hour, the cows in the other pen were then moved out for milking. Because the indirect methods depend highly on CO₂ and moisture production rates by the cows, this cow movement for milking affects AER measurements by these two indirect methods. Significant errors in computing AER and thus the emission rates of pollutants may occur if cow movements during milking periods are not accounted for in the computations. Fig. 2.12 represents barn AER determined by the three different methods for a typical day in March. Evidently, the AER during milking periods were significantly overestimated by the indirect methods compared to steady AER by the direct method.
In general, CO₂ and H₂O production decrease with decrease of cow numbers in the barn, which implies narrower or less differences in the concentrations of CO₂ and H₂O between indoor and outdoor air. Effectively, random errors are significantly exaggerated. For example, the differences between indoor and outdoor CO₂ and H₂O levels are the denominators in equations (2.9) and (2.12), for computation of AER using CO₂ and H₂O mass balances, respectively. A unit of random error will have a greater effect when these differences are smaller compared to when they are larger, which skews or distorts AER by either method. Previous research attributed these erratic AER to increased animal activity in the building, disturbance of air flow pattern and decreased differences in indoor outdoor concentrations (Marik and Levin, 1996; Snell et al., 2003; Wang et al., 2006; Ngwabie et al., 2009). The current study suggests that the difference between indoor and outdoor concentration was the major culprit.
Table 2.3, for example, presents the proportion of acceptable AER based on hourly means during 28 d of measurements using the daily 4:00 pm milking session. The means and standard deviations of AER by direct method for each day were considered as the reference statistics for computing the proportions presented in Table 2.3. The AER determined by indirect methods were considered outliers when they fell outside of three standard deviations from the mean. The acceptable data with the H$_2$O-balance method were only 48% during milking time, while the acceptable data with the CO$_2$-balance method were similar at 57%. Clearly, AER and emissions data collected using any of these indirect methods during milking time may be unreliable and should be discarded or interpreted or used cautiously.

Table 2.3 Proportion of acceptable AER during the 4 to 6 pm milking time based on 28 d mean hourly data.

<table>
<thead>
<tr>
<th>Data points (7 d for four seasons)</th>
<th>AER$_{CO_2}$</th>
<th>AER$_{H_2O}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$&lt; \mu - 3\sigma$ Acceptable</td>
<td>$\mu + 3\sigma$ Acceptable</td>
</tr>
<tr>
<td>%</td>
<td>56</td>
<td>7</td>
</tr>
</tbody>
</table>

2.5. Conclusions

Air exchange rates for a NV dairy barn were determined using two indirect methods (the CO$_2$-balance and H$_2$O-balance methods) and a direct method. The effects of pertinent factors on indirect methods were also evaluated. The following conclusions were based on data obtained in these studies.

(1) Barn AER obtained by CO$_2$-balance method with integration time of 24 h were not significantly different from those obtained with the direct method. Shorter integration times (1, 2, and 12 h) resulted in significantly different AER. The converse was true with the H$_2$O-balance
method, which yielded AER values not significantly different from those with the direct method at integration times of 1 h and 2 h and values that were significantly different from those with the direct method at integration time of 12 h and 24 h. The mean AER in barn ranged from 11 to 39 h\(^{-1}\) across all study periods and methods. The CO\(_2\)-balance method, in general, tended to overestimate the AER, while the H\(_2\)O-balance method tended to underestimate the AER. The CO\(_2\) production rate was estimated at 0.178 m\(^3\) h\(^{-1}\) hpu\(^{-1}\), the correction factor \(K_s\) was estimated at 0.65, for our study barn, using the 24-h data averaging.

(2) Barn AER increased with wind speeds irrespective of the measurement methods adopted. The differences in barn AER obtained by the indirect methods and the direct method increased with wind speeds.

(3) At a given wind direction, the method had no significant effect on the AER, however, wind directions had a significant effect on AER regardless of the methods used. The mean barn AER were significantly lower when prevailing wind direction was normal to the smaller endwalls rather than to the long sidewalls. Furthermore, the differences between the CO\(_2\)-balance method and direct method varied significantly across wind directions.

(4) Both indirect methods were unreliable for estimating barn AER during milking time and when indoor-outdoor temperature, absolute humidity and CO\(_2\) concentration differences were less than 1.0°C, 0.3 g of water m\(^{-3}\) and 100 ppm, respectively.
2.6. References


CHAPTER THREE

POTENTIAL SIMPLE METHODS FOR DETERMINING AIR EXCHANGE RATES IN NATURALLY VENTILATED DAIRY BARNS

3.1. Abstract

This research investigated two simple direct methods and one simple indirect method for estimating air exchange rate (AER) in naturally ventilated (NV) dairy barns. The first simple direct method was based on measurement of wind speed at a local weather tower (WT) installed at a height of 11 m. The second simple direct method involved measurements of airflow speed at only one location in the barn, while the third method (indirect) was comprised of indoor-outdoor CO₂ concentration measurements. The correlations of determination between airflow velocities at respective barn openings and the corresponding wind velocities at the WT were statistically strong ($R^2 = 0.46$ to 0.91), with ventilation coefficients ($C_V$) ranging from 0.33 to 0.87. However, after accounting for the effect of wind direction, the mean windward $C_V$ was 0.74±0.29, the mean parallel $C_V$ was 0.54±0.20, and the mean leeward $C_V$ was 0.40±0.20. These $C_V$-values were used to calculate average airflow rate for each sidewall for different wind directions. The estimated barn AER by the simple method correlated well with reference barn AER ($r = 0.78$). Barn AER was also determined accurately with one-velocity measurement near the center of the barn using correction factors ranging between 2.3 and 2.6. The results from this study indicated no significant differences between perimeter sampling regime and indoor-outdoor sampling regime when determining barn AER using the CO₂-balance method. The indoor-outdoor sampling is thus more cost-effective compared to perimeter sampling that requires significantly more gas analyzers.
**Key words:** Airflow measurements, ultrasonic anemometer, ventilation coefficient, ventilation correction factor, CO₂-balance.
3.2. Introduction

Naturally ventilated (NV) buildings are characterized by numerous large openings, which ensure cost-effective ventilation necessary for optimal animal productivity (Kavolelis et al., 2008). Natural ventilation, however, is widely used in livestock housing in mild climatic regions (Wu et al., 2012a; Kiwan et al., 2013; Joo et al., 2014). The exhaust ventilation air is laden with a variety of gases produced within animal housing, which end up degrading air quality. Deposition of NH$_3$, for example, may cause soil acidification and eutrophication in surface water bodies (Bobbink et al., 1998). Ammonia in the air is also a precursor for the formation of fine particulate matter, which not only impairs visibility (Tsai et al., 2014) but also may cause respiratory problems in the human population. Methane, nitrous oxide, and carbon dioxide are greenhouse gases, which are associated with negative impacts on global climate (Lashof and Ahuja, 1990). Unfortunately, the quantification of gaseous emissions from NV livestock buildings is difficult because of the complexity of the determination of air exchange rates (AER) (Bjerg et al., 2013). Unlike mechanically ventilated buildings, the openings in NV buildings are larger, and airflows through these openings vary widely both spatially and temporally.

Techniques for measuring AER in NV animal buildings include direct and indirect methods. The most direct method of determining AER is to measure representative air velocities at all the ventilation openings. Local ventilation rates are then estimated as the product of average measured velocities and the respective opening areas (Ogink et al., 2013). Air exchange rates (AER) are then calculated by dividing the total air inflow rates for the whole barn by the volume of barn (Kiwan et al., 2012; Joo et al., 2014). The advantage of direct methods is their ability to measure AER at high frequency with minimal interferences from animal physiology or behavior. However, high initial and operation costs limit routine use of direct methods in the
field measurements. Joo et al. (2014; 2015) used a total of 16 ultrasonic anemometers (sonics) installed at select points at respective openings, to determine AER in a dairy barn. At the current retail price of $3,000 per sonic, this is a substantial capital investment especially when considering the additional costs of accessory hardware, operation, and maintenance.

Researchers have presented numerous AER measurements in NV greenhouses and civil buildings (Larsen, 2005; Teitel et al., 2008; Molina-Aiz et al., 2009; López et al., 2012), but important knowledge gaps about AER measurements exist in animal buildings which have numerous large openings different from greenhouses (Flourentzou et al., 1998; Kiwan et al., 2012; Fiedler et al., 2013). The Joo et al. (2014) preliminary research indicated good correlations between wind velocities measured by a weather tower (WT) installed at a height of 11 m and those measured with sonics mounted on external barn-walls. These results suggested that a system comprising a weather tower station and one sonic mounted in the middle of each wall could potentially be sufficient for measuring barn AER. Previous research also showed good linear correlations between wind speed inside a NV building and both external wind speed and AER (Wang et al., 1999; Wu et al., 2012b). However, these two hypotheses, which link barn AER with direct measurement of air velocities at either a local WT or internal velocities, have not received rigorous testing. Many researchers (Hellickson and Walker, 1983; ASHRAE, 2001) have introduced the concept of ventilation coefficient (or opening effectiveness) to calculate the local ventilation rate and AER, but not only were computation methods complicated but also were only tested in wind tunnel studies (Nääs et al., 1998; Verlinde et al., 1998; Yu et al., 2002). The aforementioned studies also indicated that wind direction and speed are the most influential factors governing ventilation coefficients.
Indirect methods, which do not directly measure airflow rates, include tracer gas techniques, CO$_2$-balance, H$_2$O-balance, and heat balance. Many researchers (Pedersen et al., 1998; Blanes and Pedersen, 2005; Xin et al., 2009) have thoroughly discussed the suitability and applicability of such indirect methods. Briefly, the difficulty in estimating extraneous water evaporation or condensation from dairy building floors and feeds, and heat loss through walls, floors and roofs; and thus the CO$_2$-balance method is the most feasible method for estimating AER compared to other indirect methods. The CO$_2$-balance method determines AER from the CO$_2$ concentration differences between exhausts and inlets air (Xin et al., 2009), or between indoor and outdoor (background) air (Blanes and Pedersen, 2005; Zhang et al., 2005; Kiwan et al., 2013). Because the CO$_2$ concentration difference between inside and outside the building for NV animal housing is small, accurately determining CO$_2$ concentration is critical for the CO$_2$-balance method. The most representative sampling location is usually the outlets of the buildings (Van Buggenhout et al., 2009; Ogink et al., 2013), however, defining a NV building opening as an inlet or an outlet may be challenging due to rapidly changing wind speed/direction and thermal conditions. The concentrations measured at the sampling points should represent the average concentration in the building, which is key when using the concentration differences between indoor and outdoor airs. However, all approaches assumes perfect mixing of the air inside the building, which is seldom achieved in NV building (Barber and Ogilvie, 1982, 1984). There is limited literature to guide gas sampling for estimating AER using the CO$_2$-balance method (Demmers et al., 1998; Demmers et al., 2000; Wu et al., 2012a).

The objective of the present study was to investigate three potential simple approaches for determining AER via either direct measurements of airflow rate to derive AER or indirect measurements of AER using CO$_2$-balance method in NV dairy houses. The first simple direct
method was derived from measurements of air velocities simultaneously at the WT and sonics mounted at selected barn openings. The other simple direct method was developed from measurements of air velocities by sonics mounted within the barn rather than a local WT. The simple indirect method (CO₂-balance method) was based on indoor-outdoor sampling as opposed to perimeter sampling.

3.3. Materials and Methods

3.3.1. Study Houses and Site Description

These measurements were carried out in two NV dairy houses on a commercial dairy operation located in central Washington, in the Pacific Northwest of the U.S. The NV system, for each barn, consisted of four wall openings and a ridge opening running along the length of the roof in the middle. All the openings were fully open during the time of the measurements.

Fig. 3.1 shows the layout of this dairy. Barn 1 (B1) and barn 2 (B2) were selected for studies reported in this paper. The sidewalls and the ridge of the buildings ran from east (90°) to west (270°). B1 and B2 were situated 55 m apart. The On Farm Instrument Shelter (OFIS) was located halfway between B1 and B2. Each barn had two equal pens separated by a concrete pad feed alley (Fig. 3.2a). Except for the north pen of B1, all the other pens consisted of three rows of individual freestalls. The cows in B2 were completely contained within the barn except during milking times. The north pen of B1 had an open floor plan (no stalls) with dirt floor, while the north sidewall was also completely open, allowing cows to move freely in and out of the north pen and the dry lot to the north of B1. Table 3.1 offers a detailed description of the dimensions and other features of individual barns.
Figure 3.1 An aerial view of the research site showing locations of study barns (B1 and B2) (Joo et al., 2014).

Table 3.1 Pertinent information for each barn during the respective measurement campaign periods.

<table>
<thead>
<tr>
<th>Barn</th>
<th>B1</th>
<th>B2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dimensions</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Length, m</td>
<td>183</td>
<td>213</td>
</tr>
<tr>
<td>Width, m</td>
<td>31</td>
<td>39</td>
</tr>
<tr>
<td>Height of eave, m</td>
<td>3.61</td>
<td>3.61</td>
</tr>
<tr>
<td>Height of open ridge, m</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>Width of open ridge, m</td>
<td>1.57</td>
<td>1.85</td>
</tr>
<tr>
<td>Volume, m$^3$</td>
<td>41940</td>
<td>63400</td>
</tr>
</tbody>
</table>
3.3.2. AER Measurements with Direct Methods

To determine barn reference AER, air velocities, normal to each opening, were measured simultaneously with 16 three-dimensional ultrasonic anemometers (3-D sonics) (Model 81000, R.M. Young Co., Traverse City, MI) installed (in 2009) at select points on the barn openings (Joo et al., 2014) (Fig. 3.2a, 3.2b). The air velocities were measured as a time series of single wind vector components on the x-, y- and z-axes (u, v, and w) with a time resolution of 1 Hz. According to the manufacturer’s specifications, the accuracy of the sonic is < 1% root mean square for wind speed and 2° for wind direction when wind speed is less than 30 m s$^{-1}$. Each of the 16 sonics was positioned such that positive velocities indicated air flows out of the barn, while negative velocities indicated air flows into the barn as shown in Fig. 3.2a, 3.2b.

Monitoring in B1 was terminated in 2010 and only B2 was monitored in 2013 and 2014. Besides the original 16 sonics retained to monitor B2, a new system was established including 6 sonics (labeled: A, B, C, D, E, and F) inside B2 and 1 sonic (labeled: WT) on the roof of B2 at a height of 11 m (Fig. 3.2a, 3.2c). All 7 sonics were orientated northward such that the positive v component with wind from the north. Sonics A, E, and F were located at a height of 3 m above the floor, while sonics B, C, and D were aligned along a vertical support at 3, 5, 7 m above the ground, respectively.

External local wind velocities were measured by a cup wind anemometer (labeled: wt) (Model 03002VM Wind Sentry, R.M. Young Co., Traverse City, MI) on the roof of B1 during 2009 and 2013, and by a sonic (labeled: WT) on the roof of B2 in 2014. Interior and exterior air temperatures were measured by RH-temperature probes (NOVUS Model RHT-WM, Novus Electronics, Porto Alegre, Brazil) situated near the center of B1 and B2 at a height of approximately 8 m and on the roof of B1 at a height of 11 m, respectively. All these parameters
were measured automatically each second (1 Hz) and averaged and recorded every minute using custom-developed software “AirDAC” (air quality data acquisition and control) (Ni and Heber, 2010).
Figure 3.2 Wind velocity and temperature measurement setup: (a) plan view during all three years, (b) around B1 and B2 in 2009 (end view), (c) around and inside B2 during 2013 and 2014 (end view), and (d) sonic orientation.

3.3.3. AER Measurements Using CO$_2$-Balance Method

To determine barn AER with indirect method, CO$_2$ concentrations were measured using a photoacoustic IR multigas monitor (Model 1412, Innova AirTech Instruments, Ballerup, Denmark). Fig. 3.3 shows the schematic of gas sampling locations in B2. During the first round of measurements in 2009, 16 sampling ports were located adjacent to each of the 16 sonics around the perimeter of B2 (hence, the “perimeter sampling”). In the second round of measurements in 2013, eight sampling ports were mounted inside the B2 and one sampling port outside of B2 (hence, the “indoor-outdoor sampling”).
For the perimeter sampling, the four sampling ports at each sidewall or the ridge, and the two sampling ports on each endwall were pooled together to yield composite sample lines for each endwall, sidewall, and the ridge. The sample lines in the perimeter sampling system thus summed up to ten: five for B1 and five for B2. Samples from all locations, for concentration measurements, were drawn sequentially at intervals of 10 min and it thus took 100 min to complete a sampling cycle. The indoor-outdoor sampling, on the other hand, consisted of four air sampling ports distributed equally along the centerlines of each of the south and north pens of B2 and mounted at approximately 3 m above the floor (Fig. 3.3). The four sampling ports in each pen were combined into one, resulting in two composite sample lines, each for one half of B2. Another air sampling port for sampling ambient air was placed outside of B2 to the north side of the OFIS, at approximately 3 m off the ground. Effectively, this resulted in a total of 3 sample
The sampling time for each sample line was thus extended to 20 min during any given 60 min measurement cycle. The collection, conveyance, and analyses of gases were described detailed in Joo et al. (2014), Joo et al. (2015) and Ni and Heber (2010).

3.3.4. Data Analysis

The data used in the analyses in this paper were from a series of measurement campaigns conducted: one week (7 d) in B1 and B2 during summer 2009 (07/01 – 07/07); one week in B2 during summer 2013 (07/04 – 07/10); one month (31 d) in B2 during summer 2014 (07/15 – 08/14, except during system maintenance on 08/12); and one week in B2 during autumn 2014 (09/04 – 09/10). Data points (hourly mean barn AER) falling outside one and half of the interquartile range (1.5×IQR) were deemed outliers and were not used in subsequent analyses (Sancho et al., 2014; Joo et al., 2015). However, all the raw data for the direct measurement methods were valid.

3.3.4.1. Simple Direct Method 1

The airflow rate at the barn inlets can be calculated from the wind speed at a reference height, the total area of inlets, and the ventilation coefficient using a generalized Eq. 3.1 (Hellickson and Walker, 1983; Verlinde et al., 1998; ASHRAE, 2001).

\[ Q = C_V A_{inlet} u_{ref} \] (3.1)

In equation 3.1, \( Q \) is airflow rate (m\(^3\) s\(^{-1}\)), \( C_V \) is ventilation coefficient (dimensionless), \( A_{inlet} \) is free surface area (m\(^2\)) of the inlet opening, and \( u_{ref} \) is free wind speed (m s\(^{-1}\)) measured usually at a reference height of 10 m. In the current study, the reference height was 11 m, which was the height of the local WT from the ground and approximately 1.5 m above B1 roof.
In order to determine the ventilation rate using Eq. 3.1, however, the ventilation coefficient \( C_v \) must be available or determinable. Our hypothesis, in this approach, was that empirical values of \( C_v \) can be used to determine natural ventilation rates for geometrically similar dairy barns under comparable environmental and topographical conditions using data collected at a local WT. The first step towards developing \( C_v \), for each air inlet or outlet, was to determine airflow rates (Q) using the sonics mounted at the respective inlets and outlets. Second, the \( C_v \) for each inlet or outlet were determined by dividing the respective inlet airflow rate by the product of the corresponding \( u_{ref} \) provided by the WT and respective inlet area (Eq. 3.2). This step was accomplished using data collected in B2 over a month during summer 2014.

\[
C_{v_{El}} = -\bar{v}_{El} A_{inlet(E_i)}/\bar{u}_{WT} A_{inlet(E_i)} = -\bar{v}_{El}/\bar{u}_{WT} \tag{3.2a}
\]

\[
C_{v_{Wi}} = \bar{v}_{Wi}/\bar{u}_{WT} \quad C_{v_{Sj}} = \bar{v}_{Sj}/\bar{v}_{WT} \quad C_{v_{Nj}} = -\bar{v}_{Nj}/\bar{v}_{WT} \quad C_{v_{Rj}} = \bar{v}_{Rj}/\bar{w}_{WT} \tag{3.2b}
\]

Where: \( C_{v_{El}}, C_{v_{Wi}}, C_{v_{Sj}}, C_{v_{Nj}}, \) and \( C_{v_{Rj}} \) are the \( C_v \) of perpendicular air velocities at each sonic versus corresponding wind velocities at the WT, respectively; \( \bar{v}_{El}, \bar{v}_{Wi}, \bar{v}_{Sj}, \bar{v}_{Nj}, \) and \( \bar{v}_{Rj} \) are the mean air velocities (m s\(^{-1}\)) perpendicular to the openings of east, west, south, north, and ridge for the 16 sonics, respectively, while the subscripts designate the 16 sonics, \( i = 1, 2 \), and \( j = 1, 2, 3, 4 \); \( \bar{u}_{WT}, \bar{v}_{WT}, \) and \( \bar{w}_{WT} \) are the horizontal, longitudinal and vertical component (m s\(^{-1}\)) for each wind vector at the WT; the positive and negative symbols were derived from the setups or orientations of the sonics according to Fig. 3.2. The velocities at the east end wall and north sidewall were negative, while those for the west end wall, south sidewall, and ridge were positive. Finally, \( A_{inlet(E_i)} \) is the opening area (m\(^2\)) associated with sonic \( E_i \).
Since airflow at the ridge was less dependent on wind direction, the average $C_v$ for the ridge ($\overline{C_{VR}}$) was the average of ventilation coefficients ($C_{VRi}$) for the four ridge sonics (labeled: R1 to R4) according to Eq. 3.3.

$$\overline{C_{VR}} = \frac{1}{4} \sum_{j=1}^{4} C_{VRj}$$ (3.3)

To account for the effect of wind direction on the $C_v$ for the four sidewall openings, the data for each sonic were sorted into the three categories: windward, leeward, parallel wind (a wind direction parallel to the opening in question), and the corresponding $C_v$ for each sonic for the three wind directions were calculated. For example, for the two sonics (E1 and E2) mounted on the east end wall, the parallel winds were southerly winds ($135^\circ - 225^\circ$) and northerly winds ($315^\circ - 45^\circ$), the windward was easterly winds ($45^\circ - 135^\circ$), and the leeward was westerly winds ($225^\circ - 315^\circ$). The average $C_v$ for the 12 sonics mounted on the barn-walls were calculated separately for windward, leeward, and parallel wind according to Eq. 3.4.

$$\overline{C_{VW}} = \frac{1}{12} \sum_{i=1}^{12} C_{VWi} \quad \overline{C_{VL}} = \frac{1}{12} \sum_{i=1}^{12} C_{VLi} \quad \overline{C_{VP}} = \frac{1}{12} \sum_{i=1}^{12} C_{VPi}$$ (3.4)

Where: $\overline{C_{VW}}$, $\overline{C_{VL}}$, and $\overline{C_{VP}}$ are average ventilation coefficients for 12 windward ventilation coefficients ($C_{VWi}$), 12 leeward ventilation coefficients ($C_{VLi}$), and 12 parallel winds ventilation coefficients ($C_{VPi}$) at sonic labeled $i$.

The average $C_v$ were used to calculate the average airflow rate for each opening according to wind direction for that period. For easterly winds as an example, the average airflow rate for each wall or opening was calculated according to Eq. 3.5:

$$Q_E = -\overline{C_{VW}} \bar{u}_{WT} A_E \quad Q_W = \overline{C_{VL}} \bar{u}_{WT} A_W$$ (3.5a)

$$Q_S = \overline{C_{VP}} \bar{v}_{WT} A_S \quad Q_N = -\overline{C_{VP}} \bar{v}_{WT} A_N$$ (3.5b)

$$Q_R = \overline{C_{VR}} \bar{w}_{WT} A_R$$ (3.5c)
Where: $Q_E$, $Q_W$, $Q_S$, $Q_N$, and $Q_R$, are the airflow rates (m$^3$ h$^{-1}$) through the east, west, south and north barn-walls, and the ridge for easterly winds; and $A_E$, $A_W$, $A_S$, $A_N$, and $A_R$ are the respective areas (m$^2$) of east, west, south, and north barn-walls, and ridge openings. Negative airflow rates denote air inflows, while positive airflow rates indicate air outflow. The barn AER was the quotient of the total inflow rate and the volume of the barn (Eq. 3.6).

$$AER_{WT} = \frac{\sum_{j=1}^{5} |Q_{inflow}|}{V_{barn}}$$  \hspace{1cm} (3.6)

Where: $AER_{WT}$ is air exchange rate (h$^{-1}$) estimated by simple direct method 1 using WT data, $Q_{inflow}$ is the inflow rate (m$^3$ h$^{-1}$) for opening j, and $V_{barn}$ is the volume of the barn (m$^3$).

The method was validated with data collected from another barn (B1) during one week in summer 2009. The hourly average AER for B1 were computed using another set of 16 sonics mounted at all the inlets in B1 during the same period. The AER values obtained with the developed model (Eq. 3.2 – 3.6) for the same one week in summer 2009 were then compared with the reference AER obtained with the 16 sonics. To evaluate the performance of the method, the relative measurement error ($E$) was used according to Eq. 3.7, where an $E$ of < 10% is considered acceptable (Van Buggenhout et al., 2009; Van Overbeke et al., 2014).

$$E = \frac{AER_{predicted} - AER_{reference}}{AER_{reference}} \times 100$$  \hspace{1cm} (3.7)

3.3.4.2. Simple Direct Method 2

The hypothesis of this approach was that a single 3-D sonic if positioned properly in the barn would be sufficient for estimating barn AER. The AER estimated by each sonic, for example, was calculated as the sum of three airflow rates as shown in Eq. 3.8:
\[ AER_{\text{Sonic}_i} = \frac{ABS(\bar{u})A_R + ABS(\bar{v})A_N + ABS(\bar{w})A_R}{v_{\text{barn}}} \quad (3.8) \]

Where: \( AER_{\text{Sonic}_i} \) is the air exchange rate (h\(^{-1}\)) estimated by a sonic placed inside the barn, and \( \bar{u}, \bar{v}, \bar{w} \) are the hourly averages of horizontal, longitudinal and vertical components for each wind velocity (m s\(^{-1}\)) provided by a sonic in question, respectively.

The linear regression relationships between reference AER obtained with 16 sonics and predicted AER by each sonic at six positions inside the barn (labeled: A to F) were investigated using data measured continuously in B2 for one month during summer 2014. The coefficients of determination (R\(^2\)) for each sonic were used to select the most suitable positions. The slope provided the necessary correction coefficient (\( C_C \)) as shown in the linear regression equation (Eq. 3.9).

\[ AER_{\text{reference}} = C_C AER_{\text{Sonic}_i} \quad (3.9) \]

Where: \( AER_{\text{reference}} \) is air exchange rate (h\(^{-1}\)) estimated by 16 sonics mounted at all the inlets in the barn, and \( AER_{\text{Sonic}_i} \) is air exchange rate (h\(^{-1}\)) predicted by sonic \( i \).

To validate this approach, another dataset was collected for one week in B2 during a different period (Autumn 2014). The AER values predicted by the selected optimally positioned sonics were multiplied with the previously determined values of \( C_C \) for statistical comparison with the reference barn AER.

3.3.4.3. Simple CO\(_2\)-Balance Method

The reliability of this approach depends on the accuracy of determining CO\(_2\) production by the housed animals. The CO\(_2\) production is determined by the difference between concentrations in the outgoing and incoming air samples. The effects of the two sampling
regimes (perimeter sampling and indoor-outdoor sampling) for determination of the CO$_2$ balance were evaluated in this study. However, because the two sampling regimes were not conducted simultaneously, the performances of CO$_2$-balance method under these two sampling regimes were compared against reference barn AER measured by the 16 sonics. Barn AER using the CO$_2$-balance method was calculated using Eq. 3.10 (Blanes and Pedersen, 2005; Zhang et al., 2005; Xin et al., 2009; Kiwan et al., 2013):

$$AER_{CO_2} = \frac{C_{prod}}{10^{-6}(C_{outlet}-C_{inlet})} = \frac{C_{prod}}{10^{-6}(C_{indoor}-C_{outdoor})}$$ (3.10)

Where: $AER_{CO_2}$ is the air exchange rate (h$^{-1}$) estimated by the CO$_2$-balance method; $C_{prod}$ is the CO$_2$ production on a 24-h basis (m$^3$ h$^{-1}$), and the calculation was well documented in the literature (Pedersen et al., 1998; CIGR, 2002; Blanes and Pedersen, 2005; Zhang et al., 2005); $C_{outlet}$ and $C_{inlet}$ are the mean CO$_2$ concentrations (ppm) in the outlets and inlets air (perimeter sampling), respectively; while $C_{indoor}$ and $C_{outdoor}$ are the CO$_2$ concentrations (ppm) in the indoor and outdoor air (indoor-outdoor sampling), respectively.

The validation for AER by the CO$_2$-balance method using the perimeter sampling regime was conducted with AER values obtained simultaneously with direct method during one week in summer 2009. On the other hand, barn AER by CO$_2$-balance method using indoor-outdoor sampling regime were validated with AER estimated by direct method based on another one-week dataset simultaneously collected in summer 2013. The absolute differences between CO$_2$-balance method and direct method for these two different periods were evaluated with the t-test statistic (SAS v9.2, SAS Institute, Cary, NC, USA) at $\alpha=0.05$. 

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3.4. Results and Discussion

3.4.1. Measurement Periods and Weather Information

Both the AER and emission rates in NV dairy barns are directly dependent on internal and external environmental conditions. Table 3.2 provides the meteorological data during all measurement periods. The prevailing wind directions were either from the southwest or northwest. Outside wind speed and air temperature in summer showed little variations from year to year except those during autumn 2014 were lower. The interior-exterior air temperature differences were lower during 2009 and higher during autumn 2014 possibly due to different AER resulting from different external wind speed.

Table 3.2 Statistics of climatic conditions during respective measurement campaign periods.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>External wind direction, °</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>External wind speed, m s⁻¹</td>
<td>2.3±1.9</td>
<td>2.2±1.1</td>
<td>2.0±1.2</td>
<td>1.6±1.0</td>
</tr>
<tr>
<td>Outside air temperature, °C</td>
<td>27.1±6.6</td>
<td>28.7±6.5</td>
<td>30.3±7.0</td>
<td>24.2±6.4</td>
</tr>
<tr>
<td>Temperature difference, °C</td>
<td>0.2±1.2 (B1)</td>
<td>0.6±0.8 (B2)</td>
<td>1.8±1.5</td>
<td>2.2±1.7</td>
</tr>
<tr>
<td>AER, h⁻¹</td>
<td>52.3±30.2 (B1)</td>
<td>35.1±15.9 (B2)</td>
<td>35.7±14.4</td>
<td>35.3±18.2</td>
</tr>
</tbody>
</table>

* Mean ± standard deviation.

3.4.2. Simple Direct Methods

3.4.2.1 Simple Direct Method 1

During the one-month measurement campaign in summer 2014, all openings in barn 2 were open, which is manifested in low interior-exterior temperature differences (2.2±1.7 °C) due
to sufficient barn ventilation. According to ASHRAE (1993), natural ventilation created by wind speed exceeding 0.75 m s$^{-1}$ is greater than stack effect caused by temperature difference of 3°C. Thermal buoyancy effects, therefore, are usually smaller than wind effects at the low air temperature difference between inside and outside and buoyancy effects can be neglected in the NV animal buildings (Barrington et al., 1994; Kavolelis et al., 2008; Bjerg et al., 2013). Based on ambient wind velocities and temperature conditions, wind induced ventilation was predominant. In such situations, the external wind speed and wind direction constitute the most important factors governing barn AER and in-barn wind speed (Kiwan et al., 2012; Wu et al., 2012b; Fiedler et al., 2013; Joo et al., 2014). Table 3.3 shows the variation of $C_v$ for different barn wall-openings ranged from 0.33 to 0.87. The upper range of these values was slightly greater than the upper range of $C_v$ values reported in other studies. Verlinde et al. (1998) reported $C_v$ ranging between 0.068 and 0.52; while respective $C_v$ values ranging from 0.19 to 0.40 and 0.20 to 0.60 were reported in Choinière (1991) and in both ASHRAE (1981) and Hellickson and Walker (1983). Ideally the WT should be installed at least 10 m above the ground. However, the WT in this study was installed at a height of 11 m but only 1.5 m above the ridge of barn. The roof of the barn being too close to the WT may have influenced wind speed measurements, which probably explains the higher $C_v$ values obtained in the current study. The $C_v$ represents the correlations between wind speeds component perpendicular to the barn opening measured by 16 sonics and corresponding normal (to the same respective openings) wind velocities measured at WT. The wind speeds perpendicular to the openings at each of the 16 sonics were proportional or inversely proportional to the corresponding normal wind velocities at WT depending on the individual sonic’s installation orientation. The respective coefficients of determination ($R^2$) ranged between 0.46 and 0.91 suggesting that the reference wind velocity
(WT velocity) explained between 46% and 91% of the air velocities at the barn openings. The substantially lower wind speeds at perimeter of the barn compared to the reference wind speeds was consistent with those from a previous study (Fiedler et al., 2013). The decrease in air velocity at the barn openings is attributed to ground roughness, air obstacles near the ground, as well as the opening structure. The $C_V$ at two sonics (E1, E2) on the east end wall were larger compared to the $C_V$ at the other ten wall-sonics. This difference was attributed to less air obstacles on the east end of the barn. The wind speeds normal to the ridge vent (provided by sonics R1 to R4) were usually positive, which indicated that the ridge mainly worked as ventilation outlet as expected.

Table 3.3 Ventilation coefficients ($C_V$) at 16 different sonic positions in B2 from 720 data points.

<table>
<thead>
<tr>
<th>Position</th>
<th>Sonic j vs. Sonic WT</th>
<th>$R^2$</th>
<th>$C_V$</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>$v_{E1} = -0.87u_{WT}$</td>
<td>0.91</td>
<td>0.87</td>
</tr>
<tr>
<td>E2</td>
<td>$v_{E2} = -0.83u_{WT}$</td>
<td>0.83</td>
<td>0.83</td>
</tr>
<tr>
<td>W1</td>
<td>$v_{W1} = 0.52u_{WT}$</td>
<td>0.84</td>
<td>0.52</td>
</tr>
<tr>
<td>W2</td>
<td>$v_{W2} = 0.48u_{WT}$</td>
<td>0.69</td>
<td>0.48</td>
</tr>
<tr>
<td>S1</td>
<td>$v_{S1} = 0.50v_{WT}$</td>
<td>0.60</td>
<td>0.50</td>
</tr>
<tr>
<td>S2</td>
<td>$v_{S2} = 0.33v_{WT}$</td>
<td>0.66</td>
<td>0.33</td>
</tr>
<tr>
<td>S3</td>
<td>$v_{S3} = 0.40v_{WT}$</td>
<td>0.67</td>
<td>0.40</td>
</tr>
<tr>
<td>S4</td>
<td>$v_{S4} = 0.42v_{WT}$</td>
<td>0.61</td>
<td>0.42</td>
</tr>
<tr>
<td>N1</td>
<td>$v_{N1} = -0.56v_{WT}$</td>
<td>0.68</td>
<td>0.56</td>
</tr>
<tr>
<td>N2</td>
<td>$v_{N2} = -0.42v_{WT}$</td>
<td>0.64</td>
<td>0.42</td>
</tr>
<tr>
<td>N3</td>
<td>$v_{N3} = -0.61v_{WT}$</td>
<td>0.59</td>
<td>0.61</td>
</tr>
<tr>
<td>N4</td>
<td>$v_{N4} = -0.67v_{WT}$</td>
<td>0.46</td>
<td>0.67</td>
</tr>
<tr>
<td>R1</td>
<td>$v_{R1} = 0.73w_{WT}$</td>
<td>0.57</td>
<td>0.73</td>
</tr>
<tr>
<td>R2</td>
<td>$v_{R2} = 0.70w_{WT}$</td>
<td>0.58</td>
<td>0.70</td>
</tr>
<tr>
<td>R3</td>
<td>$v_{R3} = 0.64w_{WT}$</td>
<td>0.53</td>
<td>0.64</td>
</tr>
<tr>
<td>R4</td>
<td>$v_{R4} = 0.77w_{WT}$</td>
<td>0.58</td>
<td>0.77</td>
</tr>
</tbody>
</table>

There are several factors which influence $C_V$ including wind direction, wind speed, roughness of the surrounding fields, obstacles or wind breaks, and the geometry of ventilation openings in the wall (Verlinde et al., 1998). Because external wind speed had little variations
(standard deviation was 1.2 m s\(^{-1}\) from mean) during study period, and other factors remained more or less constant, wind direction was the only one important factor with respect to barn AER in this study. In this case, data for all sonics were sorted according to wind direction to account for the variation of the \(C_V\) with wind direction (Table 3.4).

Table 3.4 Influence of wind direction on the ventilation coefficients \((C_V)\) based on 720 data points.

<table>
<thead>
<tr>
<th>Position</th>
<th>(C_V)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Parallel</td>
<td>Windward</td>
<td>Leeward</td>
<td></td>
</tr>
<tr>
<td>E1</td>
<td>0.93</td>
<td>1.12</td>
<td>0.80</td>
<td></td>
</tr>
<tr>
<td>E2</td>
<td>0.86</td>
<td>1.15</td>
<td>0.76</td>
<td></td>
</tr>
<tr>
<td>W1</td>
<td>0.52</td>
<td>0.52</td>
<td>0.53</td>
<td></td>
</tr>
<tr>
<td>W2</td>
<td>0.49</td>
<td>0.48</td>
<td>0.45</td>
<td></td>
</tr>
<tr>
<td>S1</td>
<td>0.45</td>
<td>0.75</td>
<td>0.32</td>
<td></td>
</tr>
<tr>
<td>S2</td>
<td>0.24</td>
<td>0.39</td>
<td>0.34</td>
<td></td>
</tr>
<tr>
<td>S3</td>
<td>0.46</td>
<td>0.41</td>
<td>0.34</td>
<td></td>
</tr>
<tr>
<td>S4</td>
<td>0.44</td>
<td>0.48</td>
<td>0.35</td>
<td></td>
</tr>
<tr>
<td>N1</td>
<td>0.52</td>
<td>0.83</td>
<td>0.27</td>
<td></td>
</tr>
<tr>
<td>N2</td>
<td>0.35</td>
<td>0.65</td>
<td>0.21</td>
<td></td>
</tr>
<tr>
<td>N3</td>
<td>0.68</td>
<td>0.90</td>
<td>0.23</td>
<td></td>
</tr>
<tr>
<td>N4</td>
<td>0.57</td>
<td>1.16</td>
<td>0.19</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>0.54(\pm)0.20</td>
<td>0.74(\pm)0.29</td>
<td>0.40(\pm)0.20</td>
<td></td>
</tr>
</tbody>
</table>

\(^a\) Mean \(\pm\) Standard deviation.

The ventilation coefficients for windward \((\overline{C_{V_w}})\) were the highest \((0.74\pm0.29)\), those for leeward \((\overline{C_{V_l}})\) were the lowest \((0.40\pm0.20)\), and those for parallel \((\overline{C_{V_p}})\) were in the middle \((0.54\pm0.20)\). This finding was identical to those of Verlinde et al. (1998) who showed that the highest \(C_V\) occurred when wind direction was perpendicular to the wall \((\theta=90^\circ)\) and the lowest values occurred when wind direction was parallel to the wall \((\theta=0^\circ)\). Because of the little influence of wind direction on ridge airflow rates, the ventilation coefficient for ridge \((C_{V_R})\) was
0.71±0.05, which was the average of $C_v$ for the four ridge sonics according to Table 3.3. The $C_v$ presented in Table 3.4, for each wall, were used to predict barn AER according to the prevailing external wind directions for a given time.

Fig. 3.4 represents the comparison between the reference barn AER computed from the 16 sonics ($AER_{reference}$) and the predicted barn AER using the simple direct method 1 ($AER_{WT}$).

Figure 3.4 Relationship between reference B2 AER and predicted B2 AER by simple direct method 1 (summer, 2014). The black line designates linear regression, the blue long dashes below and above the regression line represent 95% confidence interval, and the red short dashes below and above the regression lines represent 95% prediction interval.

The high correlation ($r = 0.78$) between the reference and predicted AER and an excellent fit ($\alpha=1.01$) validate the suggested two-steps $C_v$ computational process. Approximately 5.1% of data points, however, fell outside of 95% prediction interval (Fig. 3.4) mainly at the high end of barn AER. According to previous research (Yu et al., 2002), higher wind speed results in lower
$C_V$ because $C_V$ is inversely proportional to the Reynolds number and frictional losses through large inlets, both of which increase with air velocity. This probably explains why the simple direct method 1 using general $C_V$ during higher wind speed resulted in higher AER values than the reference AER.

In order to validate the simple direct method 1, the same $C_V$ values determined with data from B2 were adopted for estimating AER in a different barn (B1) during a different period (summer, 2009). Fig. 3.5 shows that the simple direct method 1 predicted the hourly mean AER in B1 well ($r = 0.81$) with a small relative measurement error of 4.2% (well below the acceptable 10% range) for the entire week.

![Figure 3.5 Validation of simple direct method 1 using reference B1 AER and predicted AER obtained from WT data (summer, 2009). $AER_{WT}$ were derived using the $C_V$ values obtained from B2 data (summer, 2014).](image-url)
These results suggest that this approach is credible for estimating AER in similar barns under similar topography and environmental conditions. On the other hand, if emissions from several barns with the same locality were being investigated, then it would be sufficient to establish the $C_v$ in one of the barns and subsequently use those $C_v$ to determine AER in other barns. This way, only gas concentrations inside and outside the other barns need to be established to compute respective emissions. However, the $C_v$ depends on the flow regime, and must be systematically determined by fitting the model to experimental data (Norton et al., 2007). Therefore, additional research is necessary to investigate potential wider application of this approach.

3.4.2.2 Simple Direct Method 2

Previous research (Wang et al., 1999; Wu et al., 2012b) has suggested that internal wind speeds are strongly related to the AER within a NV house. In order to find the optimum representative air velocities, AER were calculated based on Eq. 3.8 using the air velocities at different positions in the barn. Fig. 3.6 presents the relationships between the reference AER obtained from the 16 sonics and measured AER as perceived by individual in-the-barn-sonics at six positions (A to F, see Fig. 3.2). The AER measured at four of the six locations (B, C, D, and E) were linearly and strongly correlated ($r = 0.56$ to 0.87) to the reference AER compared to the AER perceived by sonics in the other two locations (A and F) closer to the wall openings. The sonic in location C was apparently best and marked the best AER measurement points amongst the six sonics ($r = 0.87$).
Figure 3.6 Relationship between reference B2 AER and predicted B2 AER using each individual sonic (A to F) (summer, 2014).
However, all the sonics significantly underestimated barn AER based on reference barn AER. Sonics B, C, and E underestimated barn AER by 2.6, 2.4, and 2.3 times, respectively. These underestimations may be explained by the significant disruption of airflow within the barn by various obstacles (poles, fence, water troughs, cows, etc.). These results suggest that AER estimated by sonic B, C and E need correction coefficients ($C_C$) of 2.6, 2.4 and 2.3 to represent true barn AER, respectively. Sonic D, requiring a $C_C$ of 3.2, was positioned 7 m high and closer to the roof of the barn, revealing that the short proximity of the sonic to roof introduced further significant interferences on the airflow. Positioning of a sonic close to the roof was thus deemed inappropriate and sonic D was eliminated in subsequent analyses. Consequently, locations towards the center of barn laterally and vertically were found to be the most appropriate for positioning single sonics for estimation of barn AER. The respective $C_C$ for a single sonic positioned randomly near the center of the barn, fell within a fairly narrow range of 2.3 to 2.6.

For validation purposes, the performance of each optimal sonic selected from the results in the previous step was tested using data from an additional measurement campaign conducted at a different period (autumn 2014) in the same barn. The results presented in Fig. 3.7 show that the simple direct method 2 using either sonic B, C, or E adequately predicted barn AER ($r = 0.56 - 0.91$). Table 3.5 presents the sensitivity analyses for prediction of the barn AER using the two extreme $C_C$ values for a sonic positioned at either locations B, C, or E. These results show that adopting conservative value of correction coefficient ($C_C = 2.3$), the AER can be calculated with an accuracy of 6.4% or less, while adopting liberal value of correction coefficient ($C_C = 2.6$), the AER can be calculated with an accuracy within the range of 12.4% – 20.5%. The errors associated with these predictions were in the lower quartile of the relative measurement errors of 5 – 101% of barn AER by various existing methods (Van Buggenhout et al. 2009). These results,
therefore, suggest that a single sonic positioned at any one of these locations, can serve as simple and practical approaches for determining barn AER for similar barns with appropriate $C_c$ ranging from 2.3 to 2.6. The advantage of this approach is the potential to minimize the number of sampling positions and consequently decrease workload and cost of sonic installation and maintenance, but the $C_c$ probably depends on the geometry of barn and other factors. Further research is recommended to determine the effects of diverse barn configurations.
Figure 3.7 Validation of simple direct method 2 using reference B2 AER and predicted B2 AER obtained from sonics B, C, and E (autumn, 2014). \( AER_{\text{sonic}} \) were derived using the \( C_c \) values obtained from B2 data (summer, 2014).

Table 3.5 Sensitivity analyses of the choice of correction coefficients \( (C_c) \) on barn AER predicted by simple direct method 2 at locations B, C, and E based on 168 hourly mean data points.

<table>
<thead>
<tr>
<th>Position</th>
<th>( a = \frac{AER_{\text{reference}}}{(C_c \cdot AER_{\text{sonic}})} )</th>
<th>E (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( C_c = 2.3 )</td>
<td>( C_c = 2.6 )</td>
</tr>
<tr>
<td>B</td>
<td>0.96</td>
<td>0.85</td>
</tr>
<tr>
<td>C</td>
<td>1.01</td>
<td>0.89</td>
</tr>
<tr>
<td>E</td>
<td>0.94</td>
<td>0.83</td>
</tr>
</tbody>
</table>

3.4.3. Simple CO₂-Balance Method

The barn (B2) AER by CO₂–balance method calculated from perimeter sampling (summer, 2009) and indoor-outdoor sampling (summer, 2013) regimes were plotted against the corresponding reference barn AER obtained from 16 sonics in Fig. 3.8.
Effect of gas sampling regimes on the performance of CO$_2$-balance method. The linear regression equation for perimeter sampling is $y = 1.21x$, $r = 0.58$ (n = 133); and the linear regression equation for indoor-outdoor sampling is $y = 1.27x$, $r = 0.46$ (n=155).

Although these two studies were conducted at different periods, key environmental conditions (ambient wind speed and air temperature) were nearly the same with the exception of wind direction, which were mainly northwest in 2009 and southwest in 2013 (Table 3.2). The reference barn AER were also similar: 35±16 h$^{-1}$ for the week in summer, 2009, and 36±14 h$^{-1}$ for the week in summer, 2013, which ensured side-to-side comparison of the two data sets. The results indicate that both perimeter and indoor-outdoor sampling regimes overestimated AER by similar margins of 21% and 27%, respectively, which were consistent with the accuracy range of 15 – 40% for the CO$_2$-balance method reported in Van Buggenhout et al. (2009). This error is usually attributed to inaccuracy of the CO$_2$ production model. The correlation between reference AER and perimeter sampling AER ($r = 0.58$) was greater than correlation between reference
AER and indoor-outdoor sampling AER (r = 0.46). A t-test, conducted on the differences between AER by each sampling regime and the reference AER, did not indicate significant differences (P = 0.1767) between the sampling systems. Demmers et al. (1998) reported similar results for the two sampling regimes at low wind speeds (<5 m s\(^{-1}\)); noting that such wind conditions ensure a relatively better complete mixing of air in the building as opposed to short-circuiting airflows likely to occur under higher wind conditions.

The most accurate method to determine gaseous emission is to obtain continuous measurements of gas concentrations coupled with continuous AER measurements. Perimeter sampling for one barn with five sampling lines requires at least five CO\(_2\)-analyzers to obtain continuous measurements; while the indoor-outdoor sampling for one barn with three sampling lines require two CO\(_2\)-analyzers, one for ambient sampling and one for inside the barn sampling. As a compromise between cost and accuracy of AER estimate, therefore, the indoor-outdoor sampling is thus recommended instead of perimeter sampling to measure gaseous concentrations, especially under low wind speed conditions.

3.5. Conclusions

In an effort to establish practical standard methods for measuring AER in NV dairy barn, this study investigated three potential simple approaches. Methods one and two were based on direct but simpler measurement of airflow rate, while method three was based on an indirect measurement of airflow rate (the CO\(_2\)-balance). The conclusions below are based on these three studies.

(1) The simple direct method 1 by using data from a local weather tower station was found adequate for measuring AER in NV dairy houses. The relative measurement error (4.2%) was
under 10%. The effect of wind directions on the $C_v$ was $0.74 \pm 0.29$ on the windward, $0.54 \pm 0.20$ on the parallel directions, and $0.40 \pm 0.20$ on the leeward. The $C_v$ values obtained from one barn can be applied directly to determine AER in another barn with the similar geometry under similar topographical and environmental conditions.

(2) The simple direct method, which involved one-velocity measurement at locations at or adjacent to the barn center (laterally and vertically), was also deemed suitable for determining barn AER with application of correction factors ($C_c$) ranging from 2.3 to 2.6. The relative measurement errors, with this simple method, ranged between $-1.0\%$ and $20.5\%$. Further research is suggested to determine, especially, the influences of barn configurations and environmental conditions.

(3) The indoor-outdoor sampling regime was not significantly different from perimeter sampling regime for determining barn AER using the CO$_2$–balance method. The indoor-outdoor sampling regime was thus recommended for measuring gaseous concentrations in the CO$_2$-balance method, because it is more cost-effective than the perimeter sampling regime.
3.6. References


CHAPTER FOUR

PASSIVE SAMPLERS FOR MONITORING AMMONIA CONCENTRATIONS AND EMISSIONS IN NATURALLY VENTILATED DAIRY BARNS

4.1. Abstract

Emission of ammonia (NH₃) from livestock operations is a major air quality issue because of negative impacts of NH₃ on both human health and the environment. It is important to measure NH₃ emission from livestock barns in order to develop mitigation strategies, models, and inventories. However, credible and continuous measurements of NH₃ concentrations usually require expensive and sophisticated instruments. This research investigated the use of two relatively cost-effective devices for determining NH₃ concentrations in naturally ventilated (NV) dairy barns including an Ogawa passive sampler (Ogawa) and a passive flux sampler (PFS). These samplers were deployed adjacent to sampling ports of a photoacoustic IR multigas spectroscope (INNOVA), in a NV dairy barn, in six separate measurement campaigns. A 3-day deployment period was deemed suitable for both passive samplers. The correlations between concentrations determined with the passive samplers and the INNOVA were statistically significant (r = 0.93 for Ogawa and 0.88 for PFS). Compared with reference measurements, Ogawa overestimated NH₃ concentrations in the barn by ~14%, while PFS underestimated NH₃ concentrations by ~41%. Barn NH₃ emission factors per animal unit (20.6 – 21.2 g d⁻¹ AU⁻¹) based on the two passive samplers, after calibration, were similar to those obtained with the reference method and were within the range of values reported in literature.

Keywords: Natural ventilation, air quality, ogawa passive sampler, passive flux sampler, photoacoustic IR analyzer
4.2. Introduction

In the U.S., over 80% of national NH$_3$ emissions are released from agricultural operations, and ~55% is attributed to animal livestock operations (Aneja et al., 2008; EPA, 2011). Along the production chain, livestock barns, in particular, represent a major source of NH$_3$ emissions to the atmosphere due to their large footprints and abundant source of enzyme urease in the feces (Mukerjee et al., 2004; Leytem et al., 2009). Ammonia, in the atmosphere, is a precursor for the formation of atmospheric fine particular matter (Puchalski et al., 2011). In addition, ammonia deposition can cause acidification in some soils and eutrophication in surface waters (Kirchner et al., 1999). Therefore, it is important to measure NH$_3$ emission from livestock barns in order to assess emission reduction strategies, validate emission models, and obtain accurate emissions inventories (Ngwabie et al., 2009). However, quantification of emissions from naturally ventilated (NV) animal buildings, the most common type of dairy cow housing in moderate climates, is an arduous and costly exercise (Joo et al., 2014). Besides the difficulty in measuring ventilation rates, credible and continuous measurements of gas concentrations, to determine emissions in NV barns, still present considerable challenges, which includes undefined inlets and outlets and conveyance of adhesive NH$_3$ to the sampler (Rom and Zhang, 2010).

Devices for measuring NH$_3$ concentrations in air can be designated into three categories (Phillips et al., 2001; Rom and Zhang, 2010): a) rapidly responding sensors providing time series concentrations (e.g., electrochemical cells, chemiluminescence, fluorescence, photoacoustic spectroscopy, and long path optical, etc.), b) cumulative-concentration devices which provide only time-averaged values (e.g., denuders, passive samplers, and adsorption bottles, etc.), and c) instantaneous-devices which provide only snap-shot measurements. The rapidly responding devices are expensive but are notable for revealing the dynamics of gas emissions. The
cumulative-concentrations detectors are relatively inexpensive but are labor intensive and have lower detection limits. Instantaneous devices (commonly referred to as detection tubes) are relatively inexpensive but unsuitable for measuring concentrations below 2.5 ppm, which are typical in NV dairy barns (Rumburg et al., 2008; Harper et al., 2009; Joo et al., 2014).

During the last decade numerous studies have conducted measurements of NH$_3$ concentrations in dairy barns using photoacoustic infrared spectroscopes (Zhang et al., 2005; Samer et al., 2011; Joo et al., 2015). These devices provide precise and reliable results due to high-frequency measurements. However, substantial time delays occur to allow gas stabilization when switching between high and low concentration positions because NH$_3$ adsorbs on surfaces throughout the entire sampling system (Rom and Zhang, 2010), resulting in intermittent concentration measurements. Furthermore, the price of these equipment and costs of maintenance and labor are relatively high thus rendering them impractical to make multiple measurements in one barn at one dairy, let alone at more dairies, which is necessary for computation of reliable emission factors. For example, the photoacoustic IR spectroscopic method adopted by Joo et al. (2014) required five gas sampling lines and thus needed five sets of gas analyzers for each barn in order to make continuous measurements. At the current retail price of ~$50,000 for this photoacoustic IR Multigas spectroscope (Model 1412, INNOVA AirTech Instruments, Ballerup, Denmark), five sets of these spectroscopes would require an upfront investment of ~$250,000 excluding the costs of sampling hardware, operation, and routine maintenance. These categories of instruments, though credible, are rather elite making them impractical for routine monitoring of emissions in livestock barns.

Passive-sampling techniques present a viable cost-effective option for measuring NH$_3$ concentration with sufficient spatial and temporal coverage because they require no power and
are easy to manufacture, transport and deploy (Puchalski et al., 2011). Passive samplers are usually widely used in monitoring lower ambient NH$_3$ concentrations (Carmichael et al., 2003), and only limited research on use of passive samplers under high concentrations, such as livestock barns, has been conducted (Phillips et al., 1998; Losada et al., 2003; Cassel et al., 2005; Pereira et al., 2010). In this paper we report evaluation of two NH$_3$ passive samplers including a commercially manufactured unit (Ogawa passive samplers, Ogawa & Co., Inc., Pompano Beach, Florida) and a custom-made passive flux sampler (PFS) (Leuning et al., 1985). The Ogawa passive samplers (Ogawa), which use filters coated with citric acid, have been used to monitor NH$_3$ concentrations not only in ambient air (Carmichael et al., 2003), but also in open-lot dairies (Siefert and Scudlark, 2008; Leytem et al., 2009) and mechanically ventilated chicken houses (Roadman et al., 2003). However, sampler saturation restricts their deployment to short time intervals. In chicken houses with approximately 10 ppm NH$_3$, for example, Ogawa samplers were saturated in 1 h (Roadman et al., 2003), rendering their use impractical for continuous measurements necessary to determine credible emission factors. However, Ogawa samplers were deployed up to 4 d or more in an open-lot dairy with a mean NH$_3$ concentration of 0.88 ppm (Leytem et al., 2009). The foregoing suggests that Ogawa samplers may be suitable for deployment in NV dairy barns for reasonable periods because typical NH$_3$ concentrations range from 0.5 to 2.5 ppm. Passive flux samplers as described by Leuning et al. (1985) was the first form of passive flux samplers with an internal oxalic acid coating to capture NH$_3$ in a stream of air sample drawn through the sampler (Phillips et al., 2001). The PFS, a directional flux sampler, has mainly been used to measure NH$_3$ fluxes from non-point sources in agricultural field plots (Cai et al., 2002; Misselbrook et al., 2005). However, Phillips et al. (2001) argued that it was
possible to use flux samplers to determine a time-averaged concentration of NH$_3$ if suitable air velocity data were available.

The goal of this study was to assess the potential use of passive samplers (Ogawa and PFS) for respective measurements of NH$_3$ concentrations and emissions in and from NV dairy barns. The passive samplers were coupled with ventilation rates from direct measurements of airflow rates (Joo et al., 2014), for estimation of NH$_3$ emissions from a NV dairy barn. The following specific objectives were pursued to accomplish the goal: (1) determining suitable deployment times for the passive sampler; (2) investigating the performance of each passive sampler against an advanced photoacoustic IR spectroscope; and (3) determining NH$_3$ emissions from a NV dairy barn with passive samplers after calibration against reference concentration measurements.

### 4.3. Materials and Methods

#### 4.3.1. Study Site

This study was conducted on a commercial dairy in central Washington in the Pacific Northwest of the USA. This dairy operation consisted of six barns and a milking parlor. The study barn (B2) was located at the east end of the facility, and situated between two other barns (B1 in the north and B3 in the south) as shown in Fig. 4.1a. The on farm instrument shelter (OFIS) was situated between B1 and B2. The configurations of B2 (Fig. 4.1a & Fig. 4.1b) were similar to those of most NV dairy barns in Western U.S. and other regions with moderate climates. Barn 2 measured 213 m long and 39 m wide and housed ~950 milking cows (i.e. ~9 m$^2$ cow$^{-1}$). The mean live body weight of lactating cows was 657 kg (computed from the producer’s estimated mean weight of 1450 lb. per cow). The barn had two equal pens (a south pen and a
north pen) separated by a concrete feed alley. Each pen was populated with three rows of freestalls. The cows were fully contained within the barn except during milking times. Barn openings included the uncapped 185 cm ridge and the four walls (two sidewalls and two endwalls). All openings were open during the time of the measurements campaign periods during this study. Manure in the barn were flushed every 6 h using water from a secondary lagoon.

Figure 4.1 a) An aerial view of the layout of the barn on the dairy; b) internal view; and c) external view of the study dairy barn (B2).

4.3.2. Ventilation Rate and Meteorological Measurements

Barn ventilation rates were determined using a set of sixteen three-dimensional (3-D) ultrasonic anemometers (Model 81000, R.M. Young Co., Traverse City, MI) following procedures described in Joo et al. (2014). In addition to these measurements, meteorological data
(i.e., wind speed, wind direction, temperature, relative humidity, and solar radiation) were recorded at a weather tower located at a height of 11 m on the roof of B1, using a 3-D ultrasonic anemometer, a solar radiation shielded relative humidity (RH)-temperature probe (NOVUS Model RHT-WM, Novus Electronics, Porto Alegre, Brazil), and a solar radiation pyranometer (Model LI-200SL, LiCOR, Lincoln, NE). The measurement data were acquired and stored by a computer located in the OFIS via a data acquisition and control (DAC) hardware and a custom AirDAC (air emission data acquisition and control) software (Ni and Heber, 2010; Joo et al., 2014; Joo et al., 2015).

4.3.3. Ammonia Concentrations and Emissions

Ammonia concentrations inside and outside the barn were determined using the passive samplers for comparison against reference concentrations obtained with the INNOVA monitor. The ventilation rates were then coupled with the concentrations measurements to determine respective emissions. Details of the measurements and relevant computations are provided in following respective sub-sections for each device.

4.3.3.1. Reference Measurements

Reference NH₃ concentrations were measured using a photoacoustic IR multigas analyzer (Model 1412, INNOVA AirTech Instruments, Ballerup, Denmark). The air sampling system for measuring reference NH₃ concentrations consisted of nine individually filtered air sampling ports: eight air sampling ports were distributed equally along the centerlines of the south and north pens of the barn, while the ninth port was placed outside to the north of the OFIS for sampling outside the barn ambient air (Fig. 4.2).
Figure 4.2 Schematic of the gas-sampling locations in the dairy barn studied.

The nine gas sampling ports were mounted at approximately 3 m above the ground to prevent damages by the cows. The four air sampling ports in each pen were pooled together to yield two composite sample lines from the barn, resulting in three gas sample lines leading back to the multiplexer. For each composite line, adjustable custom-made airflow restrictors were utilized to balance the air sampling from each of the four sampling points. The sample lines running back to analyzer in the OFIS were insulated and kept warm using heat tapes to prevent condensation. Samples from three sampling lines were drawn sequentially to the analyzer at 3-5 L min\(^{-1}\) and at intervals of 20 min, thus taking 60 min to complete a sampling cycle. Air samples were drawn by vacuum pump into a gas-sampling manifold and into the analyzer. To ensure
linearity and precision of the analyzer, regular leak check, zero-span checks and periodical multi-
point calibrations of gas analyzer were carried out using a computerized gas diluter (Environics
Series 4040, Environics Inc., Tolland, CT) with certified zero air and NH3 calibration gases.

To determine NH3 emission rates, for a given cycle, mean NH3 concentrations were
coupled with mean barn ventilation rates, for the period in question, as shown in Eq. 4.1 and Eq.
4.2.

\[
E_{NH3} = (C_{in} - C_{out}) \cdot AER \cdot V_{barn} \cdot \frac{1}{60} \cdot \frac{1}{1000} \cdot \frac{17 \times 12.188}{T}
\]  (4.1)

\[
EF_{NH3} = \frac{E_{NH3}}{AU} \cdot 1440
\]  (4.2)

Where: \(E_{NH3}\) is emission rate of NH3 (g min\(^{-1}\)), \(C_{in}, C_{out}\) are the inside and outside concentration
measured in ppm on a volumetric basis (ppmv), respectively, \(AER\) is air exchange rate (h\(^{-1}\)),
\(V_{barn}\) is the volume of barn (m\(^3\)), \(\frac{1}{60}\) is conversion factor for switching hour to minute, \(\frac{1}{1000}\) is
conversion factor for switching mg to g, \(\frac{17 \times 12.188}{T}\) is conversion factor for switching ppm to mg
m\(^{-3}\), the temperature T to correct for temperature differences within the air samples is assumed to
be the temperatures at which volumetric concentrations are measured, \(EF_{NH3}\) is emissions factor
or cow-specific NH3 emission rate (g d\(^{-1}\) AU\(^{-1}\)), and \(AU\) is animal unit (1 AU = 500 kg body
weight).

4.3.3.2. Ogawa Passive Sampler (Ogawa) Measurements

The principle behind Ogawa samplers is diffusion of atmospheric NH3 to a reactive
surface, which chemically traps the gas according to Fick’s law of diffusion. Fig. 4.3 shows the
components of a typical Ogawa sampler, which includes two diffuser end caps, four stainless
screens, two collection pads, two Teflon rings, two Teflon disks, and the body or housing.
Figure 4.3 An exploded view of the Ogawa sampler displaying all its components (courtesy: www.ogawausa.com)

Although the device is designed with two collection pads on either end, only one pad coated with citric acid was employed because the minimum deployment period was 6 h at relatively high NH$_3$ concentration. Therefore, the mass transfer coefficient or sampling rate $m_B$ was divided by two (Roadman et al., 2003). The concentration of NH$_3$ was calculated with Eq. 4.3 and Eq. 4.4.

$$C_{NH_3} = \frac{1}{m_B} \times \frac{M}{t} = \alpha \times \frac{M}{t}$$

$$\alpha = 43.8 \times 2 \times \left(\frac{293}{T}\right)^{1.83}$$

Where: $C_{NH_3}$ = time-averaged NH$_3$ concentration (µg cm$^{-1}$ for $\frac{1}{m_B} \times \frac{M}{t}$, ppm for $\alpha \times \frac{M}{t}$), $m_B$ = mass transfer coefficient or sampling rate for the sampler (cm$^3$ min$^{-1}$), detailed derivation can be found in Roadman et al. (2003), $M$ = amount of NH$_3$ trapped (µg), $t$ = exposure time (min), $\alpha$ = sampler specific conversion factor (ppm min µg$^{-1}$) using the empirical Eq. 4.4 provided by the manufacturer, and $T$ = air temperature (K).

Prior to deployment, the disassembled components of the passive samplers were thoroughly cleaned by rinsing with deionized water, soaking in a 1 M HCl bath, rinsing again
with deionized water, and then air-drying in a clean hood. Samplers assembled in the laboratory were placed into airtight containers and transported to the site for deployment. Following exposure in the barn for the prescribed periods, the samplers were placed back into the airtight containers and transported back to the laboratory for analysis. Ammonia on the exposed pads was extracted with 8 mL deionized water over 30 min, and then shake slowly and pads were removed from deionized water. The extracts were analyzed using indophenol colorimetric method (Bolleter et al., 1961; Kothny et al., 1989) with a UV-spectrophotometer (GENESYS 10S Vis Spectrophotometer, Thermo Fisher Scientific, Madison, Wisconsin). Blanks, treated in a similar manner to deployed pads, were used to correct NH₃ concentrations obtained with the sampler. More details regarding the design, principle, deployment, analysis, and calculations for Ogawa samplers is provided in Roadman et al. (2003) and on the Manufacturer’s webpage (ogawausa.com). Ammonia mass emission rates were determined as the product of mean mass concentrations and the respective mean ventilation rates, for a given period.

4.3.3.3. Passive Flux Sampler (PFS) Measurements

The principle and assumptions behind the PFS is that air flows through the sampler at a rate linearly proportional to the external airflow velocity and that all NH₃ entering the sampler is quantitatively absorbed. Provided the PFS is pointed into the wind, the mass of NH₃ collected by the sampler during the sampling interval is defined as the mean horizontal flux density of NH₃ past a point in the vertical plane at a known downwind distance which equals to the mean vertical flux of NH₃ into the atmosphere based on the mass balance integrated horizontal flux method (Wilson and Shum, 1992). Therefore, the mean horizontal flux was directly measured from the PFS according to Eq. 4.5 and Eq. 4.6.
\[ \bar{u}c = \frac{M}{At} \quad (4.5) \]

\[ A = CA_0C_d^{\frac{1}{2}} \quad (4.6) \]

Where: \( u \) = the instantaneous horizontal wind velocity normal to the plane (m s\(^{-1}\)); \( c \) = NH\(_3\) mass concentration in excess of the background (\( \mu g \) m\(^{-3}\)), whereas the over bar represents time-averaging; i.e. \( \bar{u}c \) = the mean flux density past the reference plane during the sampling period (\( \mu g \) m\(^{-2}\) s\(^{-1}\)), \( M \) = the mass of NH\(_3\) collected in the sampler during the sampling period (\( \mu g \)), \( t \) = exposure time (s), \( A \) = effective cross sectional area of sampler (m\(^2\)), \( A_0 \) = cross-sectional area of the orifice with diameter of 7 mm (m\(^2\)), \( C \) = discharge coefficient, and \( C_d \) = drag coefficient (\( C = 0.63, C_d = 1 \) adopted from Leuning et al. (1985).

As the flux is directly measured by the PFS, the NH\(_3\) concentration in the air was then derived from dividing flux by the air velocity adjacent to the PFS using Eq. 4.7 (Misselbrook et al., 2005).

\[ C_{NH_3} = \frac{\bar{u}c}{\bar{u}} \times \frac{T}{17 \times 12.188} \times 10^{-3} \quad (4.7) \]

Where: \( C_{NH_3} \) = time-averaged concentration of NH\(_3\) (ppm), \( \bar{u} \) = average air velocity obtained with a 3-D ultrasonic anemometer located adjacent to the PFS (m s\(^{-1}\)), \( \frac{T}{17 \times 12.188} \) is conversion factor for switching mg m\(^{-3}\) to ppm, and \( T \) = air temperature (K).

Preparation and deployment of the PFS as well as data analysis followed the procedure described in Leuning et al. (1985). Briefly, prior to initial use, the interior of PFS was cleaned thoroughly with deionized water and acetone. A 40-mL solution of oxalic acid in acetone (3% w/v) was then used to coat the internal surface of the PFS. After evaporation of acetone and deposition of oxalic acid, parafilms were used to seal the sampler openings at both ends to avoid contamination. The assembled PFS were then placed into airtight containers and transported to
the site for deployment. In the barn, the PFS was mounted on its custom made bracket at a height of 2.5 m (Fig. 4.4). The parafilms were removed to initiate measurements. After the desired exposure durations, the units were again placed in the same airtight containers for transport back to the lab. To determine the mass of NH$_3$ collected, the PFS were leached with 40 ml deionized water and the leachate was analyzed using indophenol colorimetric method. Fig. 4.4 shows the deployment of Ogawa and PFS samplers in the barn as well as the relative sizes of the two samplers.

Figure 4.4 Deployed passive samplers showing the relative sizes of the Ogawa sampler against the PFS.

4.3.4. Field Deployment

4.3.4.1. Sampler Deployment Time

In order to avoid underestimating concentrations of NH$_3$ due to saturated traps from exposure of the samplers for extended periods of time, a series of Ogawa samplers were deployed adjacent to each other at the center of dairy barn where NH$_3$ concentrations were
presumably the highest, for intervals ranging from 6 h to 5 d, to determine the mass loading and optimum deployment time for this sampler. Similarly, five sets of PFS were also deployed inside the barn for time intervals between 1 d to 5 d. To accomplish this evaluation, a new set of sampler(s) was deployed at each scheduled time so that all samplers were collected together at the end of day five. For example, if the deployment were scheduled for 1, 2, 3, 4, and 5 d, a set of samplers would be deployed in day 1 for 5 d, day 2 for 4 d, day 3 for 3 d, day 4 for 2 d and day 5 for 1 d.

4.3.4.2. Concentrations in and outside the Dairy Building

Once deployment time was determined, NH$_3$ concentration measurements were performed inside and outside the barn on six different periods during summer 2014. The six periods, each lasting 3 d, commenced on 9-July, 18-July, 25-July, 1-Aug, 7-Aug, and 13-Aug. The time between measurement campaigns was used for preparation and analyses of samples. Ammonia concentration measurements in the barn were made with the INNOVA monitor, the Ogawa sampler, and PFS. A schematic of the gas sampling locations in the study barn is shown in Fig. 4.2. Duplicate Ogawa samplers were installed at 8 locations inside the barn adjacent to the gas sampling ports of the INNOVA and at one location next to the ambient gas sampling ports of the INNOVA (~30 m north of the barn), approximately 2.5 m above the ground to protect them from cows. The PFS, however, were installed at 4 locations inside the barn (two in the north pen and two in the south pen) and at one off-the-barn location adjacent to the ambient gas-sampling port, also approximately 2.5 m above the ground. Another two Ogawa samplers and one PFS were kept in OFIS during measurement campaign periods to act as blanks. Two
standard deviations from the mean concentrations from the field blanks were used as the measure of each device detection limit (DL) (Rabaud et al., 2001; Roadman et al., 2003).

4.3.4.3. Spatial Variation of NH₃ Concentration

To determine the spatial variability of NH₃ concentrations in and around the barn, 20 Ogawa samplers were deployed in a grid about 2.5 m above the ground for 1 d on two measurement campaign periods (20-Aug and 27-Aug, 2014). Of these, 12 Ogawa samplers were deployed along the four sides of the dairy barn (four for each sidewall, and two for each endwall), while the other 8 samplers (a total of four distributed in each pen) were deployed inside the barn. The PFS and the INNOVA gas sampling ports installations were not moved during this phase of study. To determine dispersion or dilution of exhausted NH₃ on leaving the barn, an array of 3 Ogawa were deployed perpendicular to the north sidewall at distances of 2, 4.6, and 10.8 m from the wall at a height of 2.5 m.

4.3.5. Data Analysis

Ammonia concentration measurements were performed inside and outside the barn using the Ogawa samplers and the PFS, and the results compared with the reference measurements. The differences in concentrations and emission rates between passive samplers and reference measurements were evaluated with the common t-test statistic (SAS v9.2, SAS Institute, Cary, NC, USA) at α= 0.05. Relative measurement error (E) (Eq. 4.8) was used to compute overall differences between passive samplers (\( \bar{X}_{\text{passive}} \)) and reference measurements (\( \bar{X}_{\text{reference}} \)) (Van Buggenhout et al., 2009; Van Overbeke et al., 2014).
\[ E = \frac{\bar{v}_{\text{passive}} - \bar{v}_{\text{reference}}}{\bar{v}_{\text{reference}}} \times 100 \% \] (4.8)

4.4. Results and Discussion

4.4.1. Environmental Conditions during Measurements

The mean environmental conditions during the six measurement campaign periods are shown in table 4.1. Average wind speed at the dairy recorded by the weather tower ranged from 1.53 to 2.20 m s\(^{-1}\). Lowest wind speeds were observed during round four experiments, while the highest wind speeds prevailed in the second round experiment. The prevailing wind direction was mainly southwesterly. The average wind speed inside the barn was 0.62 m s\(^{-1}\) (~ 0.35 times the mean external wind speed). The ratio of the inside wind speed and the external wind speed was close to the values (0.25 to 0.33) documented in Fiedler et al. (2013). The ambient air temperature ranged from 24.8 – 33.4 °C, while the inside air temperature ranged from 29.5 – 34.9 °C. The mean temperature difference was 2.6 °C. Average relative humidity (RH) ranged from 25.1% to 55.8%, and the solar radiation ranged from 255 – 334 W m\(^{-2}\).

Table 4.1 Environmental conditions at the barn site during respective measurement campaign periods.

<table>
<thead>
<tr>
<th>Measurement period (2014)</th>
<th>Ambient WS (m s(^{-1}))</th>
<th>WD (°)</th>
<th>Inside WS (m s(^{-1}))</th>
<th>Ambient air temp. (°C)</th>
<th>Inside air temp. (°C)</th>
<th>RH (%)</th>
<th>SR (W m(^{-2}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. 09 – 12 July</td>
<td>1.82</td>
<td>213</td>
<td>0.61</td>
<td>33.4</td>
<td>34.9</td>
<td>25.1</td>
<td>334</td>
</tr>
<tr>
<td>2. 18 – 21 July</td>
<td>2.20</td>
<td>241</td>
<td>0.71</td>
<td>29.2</td>
<td>31.0</td>
<td>38.1</td>
<td>276</td>
</tr>
<tr>
<td>3. 25 – 28 July</td>
<td>1.56</td>
<td>182</td>
<td>0.57</td>
<td>29.0</td>
<td>31.2</td>
<td>34.0</td>
<td>319</td>
</tr>
<tr>
<td>4. 01 – 04 Aug</td>
<td>1.53</td>
<td>228</td>
<td>0.52</td>
<td>32.0</td>
<td>34.5</td>
<td>35.8</td>
<td>255</td>
</tr>
<tr>
<td>5. 07 – 10 Aug</td>
<td>1.68</td>
<td>210</td>
<td>0.65</td>
<td>28.7</td>
<td>31.3</td>
<td>32.2</td>
<td>294</td>
</tr>
<tr>
<td>6. 13 – 16 Aug</td>
<td>1.89</td>
<td>235</td>
<td>0.63</td>
<td>24.8</td>
<td>29.5</td>
<td>55.8</td>
<td>266</td>
</tr>
</tbody>
</table>

* WS = wind speed, WD = wind direction, RH = relative humidity, and SR = solar radiation.
4.4.2. Samplers Deployment Times

The relationship between NH$_3$ mass collected in each passive sampler and sampler deployment time are shown in Fig. 4.5. In general, cumulative NH$_3$ mass in each sampler increased linearly with time during the 5-d measurement periods ($r = 0.98$ for Ogawa, $r = 0.99$ for PFS), which indicated non-saturated conditions for either sampler within this duration. The apparent slight drop in cumulative mass for Ogawa sampler, in day five, suggested that the Ogawa sampler probably could not be deployed in the barn beyond 5 d. Within the 5 d deployment period, however, the PFS did not indicate any deviation from linear increase with time, suggesting that this sampler was perhaps deployable in the barn for longer than 5 d. Based on these results, a 3 d deployment time was deemed suitable for both samplers to ensure credible concentration measurements. The selected 3-day was similar to the 4-day exposure time recommended for Ogawa samplers at a large open lot dairy with average ambient NH$_3$ concentration of approximately 620 µg m$^{-3}$ (0.88ppm) (Leytem et al., 2009). The linear increase in cumulative NH$_3$ mass collected in each sampler also indicated that NH$_3$ concentrations in the barn for all 5 d were similar. The latter may be attributed to the fairly stable environmental conditions during the sampling periods (Table 4.1). Based on their research, Ogink et al. (2008) and Mosquera and Ogink (2011) have suggested a sampling protocol for dairy barn, which ensures accurate determinations of representative emissions for a given farm unit. This protocol prescribes six sampling events distributed semi-randomly throughout the year; each event requiring a continuous 24 h measurement campaign period to capture diurnal variations. The 3 d deployment time selected for the passive sampler for determining NH$_3$ concentrations in NV dairy barns, therefore, more than satisfies the 24-h protocol requirement.
Figure 4.5 Relationships between total trapped ammonia and deployment time of the passive samplers (error bars indicate the standard deviations from mean, n = 2 for Ogawa samplers, PFS measurements were not replicated).

4.4.3. Concentration Measurements

The concentrations of ammonia in ambient air and in the barn, during six separate 3-day continuous measurement campaign periods, are shown in tables 4.2 and 4.3. In general, NH$_3$ concentrations were higher in the barn than outside the barn. The respective ratios of the INNOVA measurements to the passive sampler measurements and relative measurement errors of each passive sampler with respect to INNOVA indicated that the Ogawa sampler tended to overestimate NH$_3$ concentration (with the exception of the fourth round of measurement campaign period). Most of the Ogawa samplers relative measurement errors, however, were within the 20% acceptable range for measurements obtained with different techniques (He et al., 2014). The overestimation of the Ogawa sampler may be attributed to sampler specific
conversion factor ($\alpha$) computed from an empirical formula (Eq. 4.4). The PFS, on the other hand, generally underestimated NH$_3$ concentration in reference to the INNOVA (mean negative errors ranged from 10 to 41%) probably due to incorrect discharge and drag coefficients in Eq. 4.6, which were obtained from previous research (Leuning et al., 1985). The mean negative error for in-barn concentrations measurements with PFS was larger (30%) than that for ambient air concentrations (24%). The ambient wind speed used in the PFS computations of concentration was measured by a 3-D ultrasonic anemometer adjacent to the PFS. However, the inside wind speed used in the concentration computation with PFS was the average values measured by only four 3-D ultrasonic anemometers spread-out in the barn at a height of 3 m. The foregoing probably explained the observed differences in relative errors between in-barn and outside concentrations. Previous research has emphasized the importance of wind speed measurements for accurate determination of concentrations with the PFS measurements (Misselbrook et al., 2005).

Table 4.2 Mean 3-day NH$_3$ concentrations in ambient air determined by the INNOVA, the Ogawa, and PFS.

<table>
<thead>
<tr>
<th>Measurement period (2014)</th>
<th>Ambient NH$_3$ concentration (ppm)</th>
<th>Ratio</th>
<th>E (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>INNOVA</td>
<td>Ogawa</td>
<td>PFS</td>
</tr>
<tr>
<td>1. 09 – 12 July</td>
<td>1.12</td>
<td>1.51</td>
<td>0.94</td>
</tr>
<tr>
<td>2. 18 – 21 July</td>
<td>0.77</td>
<td>0.91</td>
<td>0.69</td>
</tr>
<tr>
<td>3. 25 – 28 July</td>
<td>1.06</td>
<td>1.31</td>
<td>0.91</td>
</tr>
<tr>
<td>4. 01 – 04 Aug</td>
<td>1.46</td>
<td>1.63</td>
<td>0.90</td>
</tr>
<tr>
<td>5. 07 – 10 Aug</td>
<td>0.89</td>
<td>1.13</td>
<td>0.53</td>
</tr>
<tr>
<td>6. 13 – 16 Aug</td>
<td>0.71</td>
<td>0.74</td>
<td>0.54</td>
</tr>
<tr>
<td>Mean ± STD</td>
<td>1.00±0.27</td>
<td>1.20±0.34</td>
<td>0.75±0.19</td>
</tr>
</tbody>
</table>
Table 4.3 Mean 3-day NH₃ concentrations in the barn determined by the INNOVA, the Ogawa, and PFS.

<table>
<thead>
<tr>
<th>Measurement period (2014)</th>
<th>In-barn NH₃ concentration (ppm)</th>
<th>Ratio</th>
<th>E (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>INNOVA</td>
<td>Ogawa</td>
<td>PFS</td>
</tr>
<tr>
<td>1. 09 – 12 July</td>
<td>1.99</td>
<td>2.06</td>
<td>1.28</td>
</tr>
<tr>
<td>2. 18 – 21 July</td>
<td>1.57</td>
<td>1.92</td>
<td>1.07</td>
</tr>
<tr>
<td>3. 25 – 28 July</td>
<td>1.79</td>
<td>2.09</td>
<td>1.22</td>
</tr>
<tr>
<td>4. 01 – 04 Aug</td>
<td>2.54</td>
<td>2.38</td>
<td>1.55</td>
</tr>
<tr>
<td>5. 07 – 10 Aug</td>
<td>1.59</td>
<td>1.88</td>
<td>1.19</td>
</tr>
<tr>
<td>6. 13 – 16 Aug</td>
<td>1.56</td>
<td>2.00</td>
<td>1.27</td>
</tr>
<tr>
<td>Mean ± STD</td>
<td>1.84±0.38</td>
<td>2.06±0.18</td>
<td>1.26±0.16</td>
</tr>
</tbody>
</table>

Fig. 4.6 shows the relationships between the NH₃ concentrations measured simultaneously, in the barn and in ambient air, with the INNOVA monitor and with the passive samplers. The results of the linear regression analyses indicated strong linear relationships between NH₃ concentrations determined with the passive samplers and with the INNOVA (r = 0.93 and 0.88 for the Ogawa and PFS, respectively). The Ogawa samplers significantly overestimated NH₃ concentrations compared to the INNOVA by approximately 14% (P < 0.0015), while the PFS significantly underestimated NH₃ concentrations by approximately 41% (P < 0.0001). The passive samplers were calibrated using the NH₃ concentrations measured with the reference INNOVA monitor collocated with passive samplers. The empirical relationships between passive samplers and INNOVA monitor are shown in the linear regression equations (0.86 for Ogawa, 1.41 for PFS).
4.4.4. Detection Limits

According to the manufacturer, the detection limit (DL) of the INNOVA monitor for NH$_3$ is 0.108 ppm. The Ogawa samplers and PFS, however, had significantly lower DLs than the INNOVA monitor (Table 4.4).

Table 4.4 Ammonia concentrations of the field blanks and the respective detection limits (DL) of the samplers (n = number of samplers).

<table>
<thead>
<tr>
<th>Sampler type</th>
<th>Mean blank ± SD (µg)</th>
<th>DL* (µg)</th>
<th>DL (ppm)</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ogawa</td>
<td>0.20±0.15</td>
<td>0.30</td>
<td>0.0057</td>
<td>12</td>
</tr>
<tr>
<td>PFS</td>
<td>17.93±4.64</td>
<td>9.28</td>
<td>0.0034</td>
<td>6</td>
</tr>
</tbody>
</table>

* DL=2 × standard deviation of the blank values
The DL for Ogawa samplers and PFS for NH$_3$ were 0.30 µg (0.006 ppm) and 9.28 µg (0.003 ppm), respectively, which were in the same order of magnitude to those documented in previous research: 0.16 µg for Ogawa samplers (Roadman et al., 2003), and 15.12 µg for PFS (Misselbrook et al., 2005).

4.4.5. Spatial Distribution of NH$_3$ Concentration

To determine the spatial distribution of NH$_3$ concentration in the barn, two 1-d studies were conducted. Due to operational problems during the second measurement (computer restart and AirDAC software not functioning), the second measurement dataset were not used in the spatial distribution analyses. The prevailing wind directions were southwest with predominantly low wind speeds and northwest with dominantly high wind speeds (Fig. 4.7a). The spatial distribution (Fig. 4.7b) shows that high NH$_3$ concentrations (> 2.0 ppm) occurred at two distinct areas in the barn, where cows aggregated during daytime to secure shade in the hot summer. Although downwind, NH$_3$ concentrations in the east section of the barn were relatively lower (< 1.8 ppm) than in other areas because cows stayed away from this area during the daytime to escape direct sunshine and thus heat. This contour plot also shows that NH$_3$ concentrations adjacent the north sidewall was lower than those next to the south sidewall. The spatial distributions of NH$_3$ concentration were in agreement with prevailing northwesterly winds with high wind speeds. The average NH$_3$ concentration determined by the INNOVA monitor was 1.5 ppm in north pen and 1.7 ppm in south pen. The PFS measurements were similar, indicating concentrations of 1.1 ppm in north pen and 2.6 ppm in south pen, validating the spatial distribution mapped with the array of Ogawa samplers. In general, NH$_3$ concentration
distribution inside the barn seems to be mainly a function of cows’ activity, sunlight, wind speed, and prevailing wind direction.

![Diagram of wind-rose and spatial ammonia concentration distribution.](image)

Figure 4.7 (a) Wind-rose during the 1-day study of spatial ammonia concentration in and around the barn, and (b) spatial distribution of NH$_3$ concentration inside and around the dairy barn.

Fig. 4.8 shows the variation in NH$_3$ concentrations at various distances, ranging between 0 and 11 m, away from one sidewall of the barn. While there were significant differences between the two sampling periods probably because of the differences in environmental conditions (temperature, humidity, wind speed fluctuations, etc.), the general trend was the same. The concentrations were high adjacent to the barn (1.3 – 1.6 ppm) and declined exponentially away from the barn possibly due to dispersion and dilution effects. Ammonia concentrations
were only slightly above the background concentrations (0.3 – 0.8 ppm) beyond 10 m. This finding is fully consistent with previously observed trends. Roadman et al. (2003) similarly observed that NH\textsubscript{3} concentrations fell to 30 \(\mu\text{g m}^{-3}\) (0.04 ppm) at distance of 20 m from a chicken house, while Fowler et al. (1998) noted that NH\textsubscript{3} concentrations fell to between 28 – 77 \(\mu\text{g m}^{-3}\) (0.04 – 0.11 ppm) at a distance of 15 m from a poultry house.

Figure 4.8 The variation of outside NH\textsubscript{3} concentration with distance from the barn with respect to the north sidewall (symbols: round one (●); round two (○)).

4.4.6. Ammonia Emission Rates

Ammonia emission rates obtained with each device (INNOVA monitor and the two passive samplers) and the relative measurement errors (E) between the passive samplers and INNOVA monitor during each round of measurement campaign period are given in table 4.5. In general, there were no significant differences in NH\textsubscript{3} emissions from barn determined with the passive samplers compared to the INNOVA monitor (i.e. \(P = 0.1831\) for Ogawa, \(P = 0.2117\) for
PFS), although the relative measurement error between pairs of measurements varied widely (from a low of 3% to a high of 48%). Ammonia emission rates, from the barn, derived from these three measurement methods in this study ranged from 13.1 – 28.2 g d\(^{-1}\) AU\(^{-1}\) with an overall mean of 20.3 – 21.2 g d\(^{-1}\) AU\(^{-1}\) based on pooled data during the entire measurement campaign period. These barn emission factors were close to the values documented in literature: 21 – 27 g d\(^{-1}\) AU\(^{-1}\) in winter and spring in Sweden (Ngwabie et al., 2009), 20 – 43 g d\(^{-1}\) AU\(^{-1}\) in summer and winter in Germany (Koerkamp et al., 1998), and also within the range of 6 – 106 g d\(^{-1}\) AU\(^{-1}\) throughout the year in Germany (Saha et al., 2014). Both samplers, therefore, are suitable for estimating NH\(_3\) concentration in dairy barns if they are calibrated over the range of concentrations common in such barns.

Table 4.5 Mean ± standard deviation (SD) of NH\(_3\) emission rates from the barn determined via the concentration measurements with the three devices (INNOVA, Ogawa, and PFS) and the relative measurement errors (E) of the passive samplers relative to INNOVA.

<table>
<thead>
<tr>
<th>Measurement period (2014)</th>
<th>Barn AER (h(^{-1}))</th>
<th>Emission rate (g d(^{-1}) AU(^{-1}))</th>
<th>E (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>INNOVA</td>
<td>Ogawa</td>
</tr>
<tr>
<td>1. 09 – 12 July</td>
<td>38.3</td>
<td>22.8</td>
<td>15.1</td>
</tr>
<tr>
<td>2. 18 – 21 July</td>
<td>37.9</td>
<td>21.4</td>
<td>27.5</td>
</tr>
<tr>
<td>3. 25 – 28 July</td>
<td>35.9</td>
<td>15.4</td>
<td>20.0</td>
</tr>
<tr>
<td>4. 01 – 04 Aug</td>
<td>32.0</td>
<td>22.8</td>
<td>17.0</td>
</tr>
<tr>
<td>5. 07 – 10 Aug</td>
<td>36.2</td>
<td>18.9</td>
<td>19.4</td>
</tr>
<tr>
<td>6. 13 – 16 Aug</td>
<td>31.3</td>
<td>20.6</td>
<td>28.2</td>
</tr>
<tr>
<td><strong>Average ± SD</strong></td>
<td><strong>35.3±3.0</strong></td>
<td><strong>20.3±2.8</strong></td>
<td><strong>21.2±5.5</strong></td>
</tr>
</tbody>
</table>

4.5. Conclusions

The potential use of two different passive samplers to measure NH\(_3\) concentrations and emissions from a NV dairy barn was evaluated as alternatives for the more complex and
expensive photoacoustic IR multigas spectroscope. The following conclusions were based on data obtained in these studies.

(1) A three-day deployment time was deemed suitable for credible determinations of concentrations ranging from 0.5 to 2.5 ppm in and around the barn with either of the two passive samplers (the Ogawa sampler and the PFS sampler).

(2) The NH₃ concentration measurements obtained with the two samplers exhibited strong linear relationships with concentrations determined with the INNOVA monitor (r = 0.93 for Ogawa sampler and r = 0.87 for the PFS). However, the Ogawa sampler overestimated NH₃ concentrations by approximately 14%, whereas the PFS significantly underestimated NH₃ concentrations by approximately 41%. The passive samplers were calibrated using corrections factors of 0.86 for Ogawa and 1.41 for PFS.

(3) The detection limits of the Ogawa sampler and PFS were 0.006 ppm and 0.003ppm, respectively, which were much lower than the 0.108 ppm for the INNOVA.

(4) The spatial distributions of NH₃ inside the barn determined with Ogawa and PFS were consistent with prevailing wind directions and mainly were dependent on cows’ activity, sunlight, and wind speed and direction. Ammonia concentrations decreased with distance away from the sidewall of the barn and were only slightly above background levels beyond approximately 10 m from the barn.

(5) The mean barn ammonia emission factors determined with all three devices (the INNOVA monitor, the Ogawa sampler, and the PFS) were similar and ranged from 20.3 – 21.2 g d⁻¹ AU⁻¹, and were within the range of values reported in previous studies.

(6) Based on the results of this study, we concluded that both passive samplers are reliable for estimation of NH₃ concentration in and around NV dairy barns, under similar management
and environment conditions. The Ogawa sampler, however, may be more preferable than the PFS because of its smaller volume, easier installation, and relatively less labor requirement for sampler preparation and subsequent ammonia extraction for analyzes.
4.6. References


CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

In this study, several novel and improved methods for measuring gas emissions from naturally ventilated (NV) livestock barns were developed and evaluated in a commercial dairy operation. First, two widely used indirect methods including the CO$_2$-balance method and H$_2$O-balance method were evaluated against a direct method for measuring air exchange rate (AER). Second, research was focused on developing two simple direct methods for determining barn AER utilizing: (1) a local weather station, and (2) a single sonic installed in the barn. The third simple method appraised two gas-sampling regimes (indoor-outdoor and perimeter samplings) for determination of barn AER via the CO$_2$-balance (indirect) method. Last but not least, this research evaluated two inexpensive passive samplers for robust but cost-effective measurement of NH$_3$ concentration in NV dairy barns. The summary and main conclusions from these studies as well as suggestions for future studies are presented in the rest of this chapter.

**Study 1. Comparison between Indirect Methods and Direct Method**

A series of field experiments were conducted on all four seasons in a year to quantify and compare AER from NV dairy barn using two indirect methods (the CO$_2$ balance and H$_2$O balance methods) and a direct method. Based on 24-h data averaging, the mean barn AER ranged from 11 to 39 h$^{-1}$ across all study periods and methods. The CO$_2$-balance method tended to overestimate the AER, while the H$_2$O-balance method tilted toward underestimating the AER. These inaccuracies were attributed to the applicable CO$_2$ and moisture production models.
Consequently, the CO$_2$ production rate and the correction factor (Ks) were estimated at 0.178 m$^3$ h$^{-1}$ hpu$^{-1}$ and 0.65 for our study barn, respectively. Results revealed that shorter integration times resulted in significantly different AER for the CO$_2$ balance method, while the converse was true with the H$_2$O-balance method. Pertinent factors that influence the performance of the indirect methods including wind speed, wind direction, temperature, humidity, CO$_2$ concentration, and milking time were also evaluated. The 1-h averaging was chosen to analyze the effects of these pertinent factors since 1-h averaging is superior for determining temporal or diurnal variations of AER. The results showed that both barn AER and the AER differences between the indirect methods and direct method increased with wind speeds. Wind directions had a significant effect on AER regardless of the methods used. Both indirect methods were unreliable for estimating barn AER during milking time and when indoor-outdoor temperature, absolute humidity and CO$_2$ concentration differences were less than 1.0 °C, 0.3 g of water m$^{-3}$ and 100 ppm, respectively.

**Study 2. Potential Simple Methods for Determining AER**

In an effort to establish practical standard methods for measuring AER in NV dairy barn, a series of field scale studies were conducted to develop two simple direct methods and one simple indirect method. The first simple direct method was based on measurement of wind speed at a local weather tower installed at a height of 11 m. This approach was found adequate for measuring AER in NV dairy houses after application of appropriate ventilation coefficients representing the relationships between wind velocity perpendicular to each opening and wind velocity at weather tower. The ventilation coefficients obtained from one barn were deemed directly applicable for determining AER in other barns with similar geometry under similar
topographical and environmental conditions. The second simple direct method involved one-velocity measurement at locations adjacent to the barn center. With the respective correction factors, ranging between 2.3 and 2.6, this method predicted barn AER well compared with reference method. The third method evaluated two gas-sampling regimes (perimeter sampling and indoor-outdoor sampling) for determining barn AER via the common CO₂-balance method. Results revealed that the indoor-outdoor sampling regime was not significantly different from the perimeter sampling regime for determining barn AER using CO₂-balance method. Therefore, the indoor-outdoor sampling regime was recommended over the perimeter sampling regime because it is more cost-effective.

**Study 3. Passive Samplers for Monitoring Ammonia Concentration**

A series of field experiments were conducted in the summer season to investigate the potential use of two relatively inexpensive passive samplers including an Ogawa passive sampler (Ogawa) and a passive flux sampler (PFS). For both samplers, a 3-d period was found to be a suitable deployment time for continuous measurement of NH₃ concentrations in NV dairy barns. These samplers were then deployed adjacent to sampling ports of a photoacoustic IR multigas spectroscope (INNOVA) continuously for 3 days in six separate measurement campaigns. The correlations between concentrations determined with the passive samplers and the INNOVA were statistically significant. Compared with reference measurements (by the INNOVA), Ogawa overestimated NH₃ concentrations by ~14%, while PFS underestimated concentrations by ~41%. After calibrations, barn emissions factors determined with all three devices (i.e., the two passive samplers and the INNOVA) were not only similar (20.3 – 21.2 g d⁻¹ AU⁻¹) but also were within the range of values reported in literature for NV dairy barns. Based on the results of this study,
both passive samplers are adequately reliable for NH$_3$ concentration determination in and around NV dairy barns. The Ogawa sampler, therefore, is perhaps more preferable than the PFS due to its smaller volume, easier installation, lower purchase price, and relative less labor requirement during preparation and NH$_3$ extraction.

**Recommended Future Work**

1. With regard to simple direct method using a local weather tower, the ventilation coefficients developed in this study need to be rigorously validated with data collected in other field studies over longer periods at multiple dairy barns located in geographically different areas.

2. With respect to simple direct method using a single sonic inside the barn, investigating the effects of diverse barn configurations on the correction factors is the next natural stage.

3. Process models (such as computation fluid dynamics) for predicting ventilation rates in NV barns are necessary and could tremendously benefit from the bulk of data generated from studies associated with this thesis. Modeling results could provide a guide in identifying representative locations for setting up sensors.

4. Further research should be directed at evaluating the use of the passive samplers in determining NH$_3$ concentration during an entire year to test their efficacy under relatively higher concentrations (especially in the winter). Use of passive sampler to determine concentrations of other gases (H$_2$S, N$_2$O, CH$_4$, and etcetera) also would be another interesting direction for future research.