Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/issn/15375110

Research Paper

Variabilities in determining air exchange rates in naturally ventilated dairy buildings using the CO_2 production model

Marcel König [a,*], *Sabrina Hempel* [a], *David Janke* [a], *Barbara Amon* [b], *Thomas Amon* [a,c]

[a] *Department Engineering for Livestock Management, Leibniz Institute for Agricultural Engineering and Bioeconomy (ATB), Max-Eyth-Allee 100, 14469 Potsdam, Germany*
[b] *Department Technology Assessment and Substance Cycles, Leibniz-Institute for Engineering and Bioeconomy (ATB), Max-Eyth-Allee 100, 14469 Potsdam, Germany*
[c] *Institute of Animal Hygiene and Environmental Health, Department of Veterinary Medicine, Free University of Berlin, Robert-von-Ostertag-Str. 7-13, 14163 Berlin, Germany*

ARTICLE INFO

Article history:
Received 7 June 2017
Received in revised form
12 June 2018
Accepted 3 July 2018

Keywords:
Livestock barn
Ammonia emission
CO_2
Natural ventilation
CO_2 balance method

Gaseous emissions from livestock buildings have been a research focus for many years. In particular, quantifying emissions from naturally ventilated buildings is not trivial because it requires accurately determining the air exchange rate (AER) and representative gaseous concentration values in the exhaust and in the incoming air. Improvements are required for the method for estimating AERs and for selecting representative sampling points and locations in naturally ventilated dairy buildings (NVB). The objective of this study was to investigate the magnitude and sources of uncertainties in calculating AERs. A long-term experiment was performed in an NVB located in north-east Germany. CO_2 concentrations were continuously measured inside the barn at eight uniformly distributed points and outside the barn at four points.

Sensitivity studies on the calculation of AER were performed by varying the indoor and outdoor sampling points, sampling duration and animal parameters used for the calculation. The sensitivity results were compared to the best available data approximation (BADA), which is based on the best knowledge of these parameters. All factors were evaluated and ordered in terms of their influence on AER calculation and uncertainty. The results show that the sampling duration and the number and location of indoor sampling points have the largest effects on AER uncertainty. Data on milk yield and days since insemination have the lowest influence on AER uncertainty. The information collected in this long-term study is very important for planning measurement campaigns in the future.

* *Corresponding author.*
E-mail address: mkoenig@atb-potsdam.de (M. König).
https://doi.org/10.1016/j.biosystemseng.2018.07.001

Nomenclature

BADA	best available data approximation
NVB	naturally ventilated barn
FTIR	Fourier transform infrared
SP	sampling point
AER	air exchange rate, [h^{-1}]
AER_c	critical AER, [h^{-1}]
D_c	critical (indoor–outdoor) differences for CO_2, [ppm]
$\sigma_{\downarrow}/\sigma_{\uparrow}$	95% confidence interval
m	mass per cow, [$kgcow^{-1}$]
N	number of cows housed in the barn, []
P_{CO_2}	production rate of CO_2, [$gcow^{-1}h^{-1}$]
p	days since insemination, [d]
Q	ventilation rate, [$m^3\ h^{-1}$]
$C_{(co_2)in}$	indoor CO_2 concentration, [$g\ m^{-3}$]
$C_{(co_2)out}$	outdoor CO_2 concentration, [$g\ m^{-3}$]
V_{barn}	barn air volume, [m^3]
y	milk yield, [$kg\ d^{-1}$]

1. Introduction

Ammonia and greenhouse gas emissions from animal confinements have been a research focus worldwide for many years (Cubasch et al., 2013). Ammonia, greenhouse gases and particulate matter have negative environmental impacts. Cattle housing systems are one of the most important agricultural sources of pollutants, and dairy cattle housing systems are primarily naturally ventilated (Steinfeld, 2006). There is a general consensus on appropriate methods for measuring emissions from mechanically ventilated buildings (Calvet et al., 2013). However, there is less consensus on methodologies for estimating ammonia and greenhouse gas emissions from naturally ventilated dairy barns. One reason for this situation is the lack of knowledge on how to estimate the air exchange rate (AER) from NVBs. Among the various direct and indirect methods developed for estimating and measuring air flow rates, as reviewed by Ogink, Mosquera, Calvet, and Zhang (2013), no method has been identified as an undisputed reference method. New approaches based on direct measurements of velocity profiles using ultrasonic anemometers have recently been developed. However, these methods either have not yet been validated by comparison with existing methods (Joo et al., 2014) or have not yet been transferred to conditions in commercial animal houses (Van Overbeke, De Vogeleer, Brusselman, Pieters, & Demeyer, 2015), Van Overbeke, De Vogeleer, Pieters, and Demeyer (2014a), Van Overbeke, Pieters, De Vogeleer, and Demeyer (2014b).

Using gas balancing to estimate the AER in NVB is a common practice. When applying this method, the estimation of the AER is highly variable, depending on the sampling position (Ikeguchi & Moriyama, 2010). Due to its good cost-benefit ratio, the CO_2 balancing method, with CO_2 as a natural tracer gas produced by the cows, has become a quasi-standard and will be investigated in this study. Compared to direct measurements in mechanically ventilated barns, gas balancing methods are likely to contain greater errors (Calvet et al., 2013). In their work, Bjerg, Zhang, and Rom (2012) introduced three important aspects that should be addressed: (1) the precision of air exchange rate estimations, (2) required length of measurement period and (3) the required number and location of sampling points. Using measurements based on only one single point is associated with large uncertainties due to the dynamic behaviour of the gas concentrations inside the barn. Therefore, whenever possible, gas concentrations in- and outside the barn should be measured simultaneously on multiple locations to improve the representativeness of the measurement values. If this is not possible, e.g. in case there is only one device with one sampling point is available, this study can help to evaluate the measured results by quantifying the uncertainty related to the used single point method. As previously discussed by Chayan Kumer et al. (2014); Hempel et al. (2016) and Mendes et al. (2015), gaseous concentrations can vary widely inside the barn depending on multiple factors, including barn geometry, occupation, wind flow patterns and inter-sensor variability; therefore, the use of several sampling locations should be favoured to represent the average concentration in the barn. Ngwabie, Jeppsson, Nimmermark, Swensson, and Gustafsson (2009) reported that the optimum number of sampling points inside a barn depends on the sampling interval, sampling time, animal distribution, building size and orientation to prevailing winds. These issues were supported by Chayan Kumer et al. (2014), who showed that the calculated air exchange rates for naturally ventilated barns strongly vary depending on the number and position of sampling points chosen. Choosing an unrepresentative sampling point will lead to a considerable increase of uncertainty in the AER estimation.

The standard uncertainty in ammonia emissions from mechanically ventilated buildings in an optimal setting is assigned as 10 % of the measurement value, whereas in naturally ventilated buildings, it may be considerably higher with significant unquantifiable biases (Calvet et al., 2013). In their study, Van Buggenhout et al. (2009) found that variations in the AER can increase to 86 % depending on the chosen sampling points within the building. They made experiments on a mechanical ventilated chamber and choose a sparsely logical sampling location for that 86 % value. On the other hand also large spatial variations occur in a large naturally ventilated barn. However, the sampling location inside the barn is important because the highly fluctuating air flow pattern within naturally ventilated buildings is strongly influenced by the outside wind and weather conditions, the size and distribution of air inlets and outlets, the building geometry and its surrounding buildings, the inside construction and the heat produced by the animals (Fiedler et al., 2014). Thus, air exchange rates in naturally ventilated buildings are directly dependent on the outside atmospheric weather or climate conditions (Ngwabie, Jeppsson, Gustafsson, & Nimmermark, 2011; Snell, Seipelt, & den Weghe, 2003) because of large openings influencing the air flow pattern within naturally ventilated buildings. Ngwabie et al. (2009) showed that long-term measurements with single sampling points may provide satisfactory results when the samplings are well positioned. For shorter measurement durations and without adequate knowledge of the optimal sampling position