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Research Paper

Indirect method versus direct method for measuring ventilation rates in naturally ventilated dairy houses

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Indirect methods are widely used for determining air exchange rates (AER) in naturally ventilated barns because they are relatively easier and cheaper than direct methods, which measure actual airflow in and out of the barns. The main goal of this study was to evaluate a common indirect method (CO_2 mass balance) against a direct method, and identify factors influencing this indirect method. The mean AER based on 24-h averaging, irrespective of method, ranged from 13 to 39 h^{-1} during the study-periods. The CO_2-balance method tended to overestimate barn AER. The cows' CO_2 production rate, in the current study, was estimated at 0.178 $m^3\ h^{-1}\ hpu^{-1}$ based on 24-h averaging. The CO_2-balance method with 24-h data averaging yielded more reliable barn AER than with shorter averaging times (i.e., 1, 2, and 12 h). The 1-h averaging, however, was chosen to analyze the effects of other pertinent factors on the CO_2-balance method to capture diurnal variations of AER. Both wind speed and wind direction had significant effects on barn AER as well as the difference between the CO_2-balance method and direct method. Barn AER, in general, increased with wind speed. The CO_2-balance method was unreliable during milking times, and when indoor–outdoor CO_2 concentration and temperature differences were less than 70 ppm and 0 °C, respectively.

1. 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 gaseous 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,

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Nomenclature

A	opening area (m^2)
A'_{CO_2}	relative animal activity
$\overline{A}_{daily}$	daily mean animal activity
$\overline{A}_{hourly}$	hourly mean animal activity
AER_{CO_2}	air exchange rate by CO_2-balance method (h^{-1})
AER_{Direct}	air exchange rate by direct method (h^{-1})
C_{in}	CO_2 concentration at the inlet (ppm)
C_{out}	CO_2 concentration at the outlet (ppm)
C_{prod}	CO_2 production on a 24-h basis ($m^3\ h^{-1}$)
d_p	days of pregnancy
HPU	1000 W of the total heat produced by the animals at 20 °C
m	body mass of the cow (kg cow^{-1})
Q	airflow through the opening ($m^3\ h^{-1}$)
T_{ind}	indoor temperature (°C)
v	perpendicular air velocity to the opening ($m\ s^{-1}$)
V	barn volume (m^3)
Y	milk yield (kg $cow^{-1}\ d^{-1}$)
ϕ_p	heat dissipation due to pregnancy (W)
ϕ_{LM}	heat dissipation due to maintenance of essential function (W)
ϕ_{MY}	heat dissipation due to milk yield (W)
ϕ_{tot}	total heat production by the animals at 20 °C (W)
ϕ^*_{tot}	total heat production corrected for temperature other than 20 °C (W)

Mosquera, Calvet, & Zhang, 2013). Natural ventilation (NV) systems in dairy barns are commonly used in regions with mild climate due to low capital and low energy demand (Andonov, Daskalov, & Martev, 2003; Joo et al., 2014; Joo, Ndegwa, Heber, Ni, Cortus, et al., 2015). However, AER in NV barns are directly dependent on atmospheric conditions (Snell, Seipelt, & Van den Weghe, 2003; Ngwabie, Jeppsson, Gustafsson, & Nimmermark, 2011). Uncertainties due to changes in meteorological conditions, therefore, further complicate estimation of AER in NV buildings.

The fundamental approach of determining AER in a NV building is direct measurement of airflow at the inlets and outlets of the building (hence: direct method). To achieve this, wind velocities at the openings are then coupled with relevant openings' areas to determine total airflow either in or out of the building. 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, Van der Maas, & Roulet, 1998; Joo et al., 2014; Kiwan et al., 2012). The accuracy of direct method mainly depends on the number of measurement points because wind velocity sensors can measure only local air velocities while wind velocities at different positions of the ventilation openings may vary significantly (Ozcan, Vranken, & Berckmans, 2007). Increasing the numbers of the sensors overcomes this drawback but also increases the cost. In previous studies (Joo et al., 2014), 16 ultrasonic anemometers (sonics) were installed at select points of the barn openings to measure air velocities at respective air inlets and outlets. This research concluded that the sum of airflows through all openings acting as inlets was the best measure of barn ventilation rate for that given period.

The AER for NV buildings are also measured using indirect methods such as tracer gas techniques (TGT), the CO_2-mass balance, H_2O-mass balance, and sensible heat balance methods. The major assumption in the TGT is complete air-mixing, but this condition is rarely achieved in NV buildings (Joo, Ndegwa, Heber, Ni, Cortus, et al., 2015). 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, Müller, Fiedler, Berg, & Brunsch, 2014). 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 direct method in mechanically ventilated barns (Blanes & Pedersen, 2005; Li et al., 2005; Xin, Li, Gates, Overhults, & Earnest, 2009). Another commonly used indirect method is the H_2O mass balances between air inside and outside buildings, which is a function of water produced by animals via respiration and evaporation from manure and forage (Blanes & Pedersen, 2005; Chepete & Xin, 2004; Pedersen et al., 1998; Samer, Ammon, et al., 2012; Samer, Berg, et al., 2012). The sensible heat balance method, which is based on animal's heat production rate, is not recommended for uninsulated buildings due to high potential errors when estimating heat transmission loss from such building (Pedersen et al., 1998). The accuracy of these indirect methods, however, depends on CO_2, H_2O, and heat produced by the housed livestock, which vary with animal weight, productivity, manure management system, and pregnancy conditions. Major sources of errors also include: unaccounted CO_2 and H_2O produced from manure, variations in meteorological conditions, locations of sampling points, and inadequacy of associated models (i.e. models not able to account for diurnal variations). 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 the most commonly used indirect method (CO_2-mass balance) against a direct method in NV dairy barns, and (ii) investigate the effects of pertinent factors (season, integration time, milking time, wind speed and direction, and differences in indoor–outdoor CO_2 concentrations and temperatures) on the CO_2-balance method.