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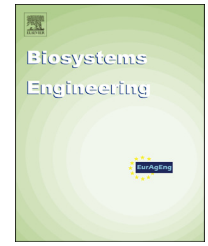

Research Paper

Spatial variability of mixing ratios of ammonia and tracer gases in a naturally ventilated dairy cow barn

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The use of the tracer gas ratio method to estimate emissions from naturally ventilated (NV) livestock barns excludes the need of monitoring ventilation rates. However, it requires accurate measurement of tracer release rate (Q_T) and a representative estimate of the mixing ratio between pollutant (P) and tracer (T) gases($\overline{[P]/[T]}$). While the quality of Q_T simply depends on using an accurate commercial mass flow controller, determination of a representative mixing ratio $\overline{[P]/[T]}$ is not trivial, since the NV livestock barn airspace presents complex movements that might be dependent on spatial vertical and cross horizontal dimensions. The goal was to assess the spatial variability of concentrations of the artificial tracer gas sulphur hexafluoride (SF_6), the metabolic carbon dioxide (CO_2) and the pollutant ammonia (NH_3), along with their mixing ratios ($[NH_3]/[CO_2]$, $[NH_3]/[SF_6]$, $[CO_2]/[SF_6]$), inside a NV dairy cow barn. The results indicated that the vertical variability of the calculated mixing ratios became more stable with increase in height, reaching approximately constant values above the animal occupied zone. Using both the metabolic CO_2 and the artificially injected SF_6 as tracer gases led to a homogeneous spread in behaviour of mixing ratios along V and HC directions. Finally, the possibility of finding a zone within the barn airspace where mixing ratios are considered to be representative for the whole barn, and the implications of applying artificial or metabolic tracers are discussed.

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Nomenclature

NV	Natural ventilation
T	Tracer gas of interest
[T]	Gaseous concentration of a tracer gas
Q_T	Release rate of a tracer gas T
AER	Air exchange rate
P	Pollutant gas of interest
[P]	Gaseous concentration of a pollutant gas
Q_P	Emission rate of a pollutant gas P
[P]/[T]	Mixing ratio between pollutant and tracer gases, both corrected for background
$\overline{[P]/[T]}$	Mean mixing ratio between pollutant and tracer gases, both corrected for background
$[NH_3]/[CO_2]$, $[NH_3]/[SF_6]$ and $[CO_2]/[SF_6]$	Mixing ratios of ammonia and carbon dioxide, ammonia and sulphur hexafluoride and carbon dioxide and sulphur hexafluoride, respectively. All concentrations corrected for background
L	Length dimension
W	Width dimension
H	Height dimension
V	Vertical direction within the barn
HC	Cross barn horizontal direction
PTFF	Polytetrafluoroethylene
ANOVA	Analysis of variance
GLM	General linear model
Y_{ij}	Measured pollutant or tracer gaseous concentration, or ratio between pollutant and tracer
Y	Gand mean concentration of pollutant or tracer gas, or ratio between pollutant and tracer throughout the experiment
V_i	Statistical effect of the vertical direction of the barn on concentrations of pollutant or tracer gases, or ratio between pollutant and tracer
HC_j	Statistical effect of the cross horizontal barn dimension on concentrations of pollutant or tracer gases, or ratio between pollutant and tracer
ε_{ij}	Independent normally distributed homogeneous random error
AOZ	Animal occupied zone

1. Introduction

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

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

According to Calvet et al. (2013), Ogink et al. (2013) and Takai et al. (2013), the tracer gas method has been considered a prominent candidate for the determination of flow rates and emissions from NV livestock buildings. Tracer gas studies are reported extensively in the contemporary literature dealing with residential, institutional (Eklund, 1999; Furtaw Jr., Pandian, Nelson, Behar, 1996; Han, Shin, Lee, & Kwon, 2011; Lim, Cho, & Kim, 2010; Santamouris et al., 2008; Xu, Luxbacher, Ragab, & Schafrik, 2013) and agricultural systems (Baptista, Bailey, Randall, & Meneses, 1999; Demmers et al., 1998; Demmers et al., 2001; Kaharabata, Schuepp, & Desjardins, 2000; Kiwan et al., 2013; Samer, Berg, et al., 2011; Samer, Loebsin, et al., 2011; Samer, Müller, Fiedler, Berg, & Brunsch, 2013; Schrade et al., 2012; Shen, Zhang, & Bjerg, 2012; Shen, Zhang, & Bjerg, 2013; Shen, Zhang, Wu, & Bjerg, 2013; Snell, Seipelt, Weghe, & Van Den, 2003; Van Buggenhout et al., 2009; Wu, Zhang, & Kai, 2012).

The theoretical foundation for tracer gas research is provided by the mixing-dilution first degree differential equation described by Barber and Ogilvie (1982), who demonstrated that in order to allow for the mass conservation of a given tracer (T) within the ventilated airspace, the constant injection rate (Q_T) of the tracer must equal the product between air exchange rate (AER, in per unit time) and the concentration of T corrected for background ([T]), in such a way that $Q_T = AER \cdot [T]$. Similarly, for a pollutant (P) being emitted to the same airspace, its emission rate Q_P can be calculated through $Q_P = AER \cdot [P]$. Hence, combining both relationships and solving for Q_P yields $Q_P = Q_T \cdot ([P]/[T])$. In other words, when using the tracer gas technique the complicated task of determining building ventilation rate in calculating gaseous emissions is suppressed/avoided. Instead, obtaining a representative mean mixing ratio $\overline{[P]/[T]}$ for the entire barn becomes essential.

The premise that both P and T present similar mixing behaviour in the region where the concentrations are to be measured might not be true when P and T have different physical properties, for instance, dissimilar molecular masses. Such discrepancies especially take effect when the mixing conditions are not ideal. Furthermore, an ideal T is the one that leads to mixing ratios that present constant values at