Research Paper

Comparison of CO$_2$- and SF$_6$- based tracer gas methods for the estimation of ventilation rates in a naturally ventilated dairy barn

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Livestock production is a source of numerous environmental problems caused by pollutant gas emissions. In naturally ventilated buildings, estimating air flow rate is complicated due to changing climatic conditions and the difficulties in identifying inlets and outlets. To date no undisputed reference measurement method has been identified. The objective of this paper was to compare CO$_2$- and SF$_6$-based tracer gas methods for the estimation of ventilation rates ($V_{RCO_2}$ vs. $V_{RSF_6}$) in naturally ventilated dairy barns both under conventional and very open ventilation situations with different spatial sampling strategies. Measurements were carried out in a commercial dairy barn, equipped with an injection system for the controlled release of SF$_6$, and measurement points for the monitoring of SF$_6$ and CO$_2$ concentrations to consider both horizontal and vertical variability. Methods were compared by analysing daily mean $V_{RCO_2}/V_{RSF_6}$ ratios. Using the average gas concentration over the barn length led to more accurate ventilation rates than using one single point in the middle of the barn. For conventional ventilation situations, measurements in the ridge seem to be more representative of the barn average than in the middle axis. For more open situations, both $V_{RCO_2}$ and $V_{RSF_6}$ were increased, $V_{RCO_2}/V_{RSF_6}$ ratios being also more variable. Generally, both methods for the estimation of ventilation rates gave similar results, being 10–12% lower with the CO$_2$ mass balance method compared to SF$_6$ based measurements. The difference might be attributed to potential bias in both methods.

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1. Introduction

Livestock production is a source of a number of environmental problems (acidification, eutrophication, loss of biodiversity) through ammonia emissions, and is a significant contributor to climate change through the emission of greenhouse gases. In order to implement and evaluate the use of technologies and practices to reduce these pollutant emissions, reliable and standardised measurement methods are required. Although gaseous emissions from livestock have been studied for decades over the world, it is acknowledged that their quantification still is a challenge. This is particularly the case for naturally ventilated buildings, prevailing in cattle systems, where estimation of air flow rates is complicated by the considerable effects of wind speed and direction, temperature, air inlet and outlet constructions as well as roof inclination angle on the air movement inside the building and the resulting net air flow rate (Calvet et al., 2013; Ogink, Mosquera, Calvet, & Zhang, 2013; Peren, van Hooff, Leite, & Blocken, 2015; Takai et al., 2013).

Among the variety of direct and indirect methods developed for the measurement of air flow rates, as reviewed by Ogink et al. (2013), none has been identified as an undisputed reference method. More recently, new approaches based on direct measurements of velocity profiles (using ultrasonic anemometers) have been developed. However, these methods either have not yet been validated by comparison against existing methods (Joo et al., 2014) or were developed in laboratory/prototype conditions and are not yet readily transferable to conditions in commercial animal houses (Van Overbeke, De Vogeleer, Brusselman, Pieters, & Demeyer, 2015; Van Overbeke, De Vogeleer, Pieters, & Demeyer, 2014; Van Overbeke, Pieters, De Vogeleer, & Demeyer, 2014). More research is therefore needed to validate their applicability and improve measurement accuracy in naturally ventilated barns. Until now, comparative studies from the literature have identified tracer gas techniques as the most robust method to investigate emissions in naturally ventilated buildings, even if improvements are required (Ogink et al., 2013; Phillips, Lee, Scholtens, Garland, & Sneath, 2001; Samer et al., 2011; Scholtens, Dore, Jones, Lee, & Phillips, 2004). The principle of the tracer gas method was extensively described in Phillips et al. (2001). It consists of releasing a tracer at a known rate, monitoring its concentration in the building and deducing the resulting air exchange rate. The tracer gas should be injected close to the emission source and disperse in a similar way as the target gas. To estimate ventilation rates (VR), concentrations measured at the sampling point(s) should be representative of the average building concentration (Ogink et al., 2013). This technique, however, assumes good air mixing conditions inside the building, which is often not the case in naturally ventilated buildings. This has resulted in some studies inferring that the uncertainty in ventilation rate estimations in very open building can exceed 50%, compared to 5–20% in mechanically ventilated buildings (Calvet et al., 2013; Zhang, Pedersen, & Kai, 2010).

The tracer used can be either artificially injected in the building (e.g. SF₆, Ikeguchi & Hideki, 2010; Scholtens et al., 2004; Schrade et al., 2012; Snell, Seipel, & Van den Wege, 2003; Zhang et al., 2005; or ⁴¹Kr, Kiwan et al., 2013; Muller et al., 2007; Samer et al., 2011, 2012) – or released as metabolic products by the animals and the manure (e.g. CO₂, Bjerg, Zhang, Madsen, & Rom, 2012; Kiwan et al., 2013; Muller et al., 2007; Ngwabie, Jeppsson, Gustafsson, & Nimmermark, 2011; Ngwabie, Jeppsson, Nimmermark, Swensson, & Gustafsson, 2009; Phillips et al., 2001; Rong, Liu, Pedersen, & Zhang, 2014; Saha et al., 2014; Samer et al., 2011, 2012; Zhang et al., 2005). The CO₂ mass balance is a particular form of tracer gas method which is considered reliable, quite simple, fast and cheap for the estimation of ventilation rates and gaseous emissions in animal housings when compared to the use of artificial tracers. The rate of metabolically produced CO₂ can be estimated from CIGR equations (Pedersen & Sällvik, 2002; Pedersen et al., 2008) using information on animal numbers and production levels. This tracer benefits from the relatively homogeneous distribution of CO₂ by animal sources throughout the building, resulting in a better mixing between the tracer and air (Ogink et al., 2013). Several uncertainties have, however, been identified which relate to the prediction of CO₂ production, such as CO₂ produced per energy unit, the amount of CO₂ emitted by manure and the location of sampling points (Samer et al., 2011).
Van Buggenhout et al. (2009) demonstrated that the outlet sampling position was the one location where, as to be expected, the ventilation rate could be estimated with the best accuracy (less than 10% error) in mechanically ventilated buildings. However, the location of exhaust air can be difficult to determine in naturally ventilated buildings as it may be subject to cross ventilation from variable directions. From an experimental study conducted by Shen, Zong, and Zhang (2012), it appeared that the optimal sampling position for indoor gas concentration measurement was found to lie close to the centre of the building, at approximately 30% of the barn height. Similarly, using one sampling point situated in the middle of the barn was shown to be equivalent to using the mean of 5 sampling points throughout the house (Bjerg et al., 2012). On the contrary, Wu, Zhai, Zhang, and Nielsen (2012) concluded from their computational fluid dynamics analysis that the mean CO2 concentration of the entire room might not accurately represent the outlet concentration in very open barns. Besides, they concluded that gas sampling positions should be located adjacent to all the openings to reduce uncertainty related to wind direction. New dairy barns, especially in Northern Europe, are more often constructed with large inlet openings, changing ventilation management from conventional ridge ventilation with restricted side inlets to combinations of cross flow and ridge ventilation. Consequently, there is a need for a better understanding of spatial variability of tracer-pollutant ratios in the building and its relation with ventilation management to improve tracer gas method reliability (Ogink et al., 2013).

The objective of this paper was to compare CO2- and SF6-based tracer gas methods for the estimation of ventilation rates in a naturally ventilated dairy barn with ridge outlet and side wall inlets. Firstly, both methods were compared when side inlet openings were reduced to a minimum. In this way, air was supposed to be well mixed and leaving the barn through the ridge, ensuring clear inlet and outlet points for sampling. The purposes of this first analysis were (a) to check whether or not both methods perform similarly under these conventional ventilation conditions and (b) to investigate the influence of horizontal (number and location of sampling points) and vertical (central axis vs. ridge) sampling strategies. Secondly, CO2 and SF6 methods were compared in more open situations (large inlet openings), when air may leave the barn both through the ridge and side openings. The applicability of these methods in barns with restricted or very open inlet configurations was discussed.

2. Material and methods

2.1. Barn description and animal management

Measurements were carried out over periods between May 2012 and December 2013 in a naturally ventilated dairy barn considered to be representative for modern dairy buildings in the Netherlands (Bunschoten, province of Utrecht, NL). A precise description of the barn characteristics can be found in Mendes, Edouard, et al. (2015). Side walls openings were protected with fabric nets (mesh 50 × 50 mm). The building was equipped with manually operated curtains to enable the farmer to modulate temperature inside the building through ventilation rate (Fig. 1). During the measurement periods, 192–201 Holstein dairy cows (131–159 lactating, 6–31 dry, 18–37 young stock) were housed in this free stall design barn which contained six rows of cubicles with paper chips used as bedding (replaced approximately every 4 month) and concrete slatted walking alleys. Feeding alleys were located on both sides of the barn (see Figs. 2 and 3). Remaining manure and urine on the slats were automatically scraped every 3 h and stored in the slurry pit under the slats. On the east side of the barn, a calving area was covered with straw litter evacuated once a year with a tractor mounted scraper (faeces manually removed daily). The lactating cows had permanent access to 3 milking robot systems. All the cows were kept in the building all year long and were fed with roughage (grass and maize silage) and concentrate. Between May 2012 and December 2013, mean live weight was 661 ± 10 kg cow⁻¹ for lactating and dry cows; young cows were not weighed regularly and were estimated to weigh 500 kg; mean milk yield per cow was 28.7 ± 1.2 kg d⁻¹.

2.2. Description of the SF6 injection system

The barn was equipped with an injection system for the controlled release of SF6. The SF6 injection system was described in detail by Mendes, Edouard, et al. (2015). A pure SF6 tank and an air compressor system were kept in a shelter placed outside of the barn. SF6 was mixed at a controlled mass flow rate of 22.4 ± 0.8 ml min⁻¹ (GFM 571, Aalborg Instruments & Controls, Orangeburg, NY, USA) with compressed air at a flow rate of 10 l min⁻¹. The mixture was channelled into the barn through polyethylene tubing (6.3 mm inside diameter) and released through injection points along both feeding fences, along the cubicles area and beyond the automatic milking systems, with a total of 114 injection points placed at approximately 0.5 m above the floor (Fig. 2). The injection points were equipped with capillary tubes and a thin plate orifice (9.8 mm internal diameter with a 217 μm diameter orifice; 0.5 mm thick) to allow equal release of a specific amount of tracer gas. The distribution of the SF6 flow over the different points within an injection line was occasionally checked measuring the pressure at individual injection points, to ensure that pressure was the same between injection lines and also between the end and the beginning of each of these lines.

2.3. Description of the CO2 and SF6 concentration measurements

The barn was provided with several spatially dispersed measurement points for the monitoring of SF6 and CO2 concentrations to consider both horizontal and vertical variability. SF6 and CO2 concentrations were monitored using different methods and sampling strategies, either based on individual sampling points, collective multi-sampling points or the average of the barn length (see Tables 1 and 2). Inside the barn, sampling took place in the centre, distributed over its full length (64 m) at two heights: 3 m above the slats, further designated as sampling of the central axis, and at 10 m above the slats and as such positioned 1 m below the ridge, further
designated as sampling in the ridge (Fig. 3). Background gas (CO₂) concentration was monitored with sampling points located outside the barn (Fig. 3). All sampling tubes were made of polytetrafluoroethylene (PTFE, 6.3 mm inside diameter).

2.3.1. Equipment for the measurement of SF₆ concentration
Five evenly distributed individual sampling points (one point every ~10 m), each with their own sampling line, were installed in the central axis of the barn (Fig. 3). Sampling in the ridge was based on one collective line with five evenly distributed inlet points (equipped with a glass capillary restricting the flow to 1000 ml min⁻¹) providing one collective multi-sampling point connected to a pump (>5000 ml min⁻¹). SF₆ concentrations were semi-continuously monitored at each individual or collective sampling points with a specific gas chromatograph analyser (Interscience CompactGC with Electron Capture Detector, see Table 2 for technical specifications) with the same measurement point measured every 40 min (Table 1) thanks to a rotary multi point selection valve.

2.3.2. Equipment for the measurement of CO₂ concentration
In the central axis of the barn, CO₂ concentrations were recorded continuously using 2 different methods and sampling strategies (see Tables 1 and 2 for descriptions). Five portable non-dispersive infrared (NDIR) type CO₂ gas sensors (model SD-GAS-025, Sensor data B. V., Rijswijk, The Netherlands) were mounted above the barn ceiling, and the CO₂ concentration was continuously recorded using a specific analyzer (Interscience CompactGC with Electron Capture Detector, see Table 2 for technical specifications) with the same measurement point measured every 40 min (Table 1) thanks to a rotary multi point selection valve.
Netherlands) were evenly distributed over the barn length (one every ~10 m) and monitored CO₂ concentration at each location every 5 min. As described in Mendes, Ogink, et al. (2015), their measurement principle is based on gas absorption of radiation at a known wavelength. The NDIR sensors were connected to a datalogger system (CR1000, Campbell Scientific, Inc., Logan, UT, USA) located in a shelter placed outside the barn (Fig. 3). In parallel, an open-path (OP) laser (model GasFinderFC, Boreal Laser, AL, Canada) was installed at one side of the barn to measure CO₂ concentrations over the whole length of the barn (64 m) every 5 min (Fig. 3, Table 1). A remote retro-reflector (prism-like mirror) was installed on the opposite wall for reflection of the laser beam back to the source. The OP-laser held a self-calibration check mechanism, including a reference calibration cell (crystal sphere containing CO₂ at known concentration; see Table 2 and Mendes, Ogink, et al., 2015 for a complete description of the CO₂ measurement systems and their calibration).

Sampling in the ridge was based on the same collective line as used for SF₆ concentration measurements, with five evenly

![Fig. 3](image)

**Fig. 3** – Position of sampling points on cross-sectional (A) and plan (B) views of the dairy cow barn either in the ridge, central axis and outside for the measurement of SF₆ concentration (squares), CO₂ concentrations (circles), temperature and relative humidity (stars). Full symbols represent collective multi-sampling lines including 5 inlet points each. Open symbols represent individual sampling points (1–5). The dotted line represents the open-path laser for the monitoring of CO₂ concentrations over the barn length. The rectangle on the left side of the barn represents the placement of the instrument shelter. In the ridge, 2 sampling lines are shown for ease of understanding (CO₂ and SF₆ concentration measurements). In reality, air was pumped via one unique multi-sampling collective line. The purge line of the pump was then split in two lines, one for CO₂ concentration measurement and one for SF₆ concentration measurement.

<table>
<thead>
<tr>
<th>Sampling site</th>
<th>Gas</th>
<th>Equipment</th>
<th>Sampling characteristics</th>
<th>Measurement frequency at each point (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central axis</td>
<td>CO₂</td>
<td>NDIR sensor</td>
<td>5 individual points</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>OP laser</td>
<td>Average of the path length</td>
<td>5</td>
</tr>
<tr>
<td>Ridge</td>
<td>SF₆</td>
<td>GC</td>
<td>5 individual points</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>CO₂</td>
<td>PAS</td>
<td>1 collective line, 5 inlet points</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>SF₆</td>
<td>GC</td>
<td>1 collective line, 5 inlet points</td>
<td>40</td>
</tr>
<tr>
<td>Outside</td>
<td>CO₂</td>
<td>NDIR sensor</td>
<td>1 individual point per side</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PAS</td>
<td>1 collective line per side, 5 inlet points</td>
<td>5</td>
</tr>
</tbody>
</table>

*NDIR sensor: non-dispersive infrared type CO₂ gas sensors; OP laser: open-path laser; GC: gas chromatography; PAS: photo acoustic multi gas monitor.*
distributed inlet points providing one collective multi-sampling point (purge line of the pump split in two lines, Fig. 3). CO2 concentrations were measured every 5 min using a photo acoustic multi-gas monitor (PAS; Innova model 1312, INNOVA AirTech Instruments A/S, Ballerup, Denmark; filter model UA0982, AirTech Instruments). Dew point temperature was also monitored by the PAS analyser in order to account for cross-interference with moisture in the air (see Table 2 and Mendes, Ogink, et al., 2015 for more technical descriptions and calibration).

Background concentrations were recorded every 5 min both using two NDIR sensors (one on each side of the dairy barn, in the middle of the barn length; Fig. 3) and two collective multi sampling lines (one on each side of the barn, each including 5 inlet points; Fig. 3) providing average measurements points for the determination of CO2 concentrations with the PAS. Both NDIR sensors and inlet points from the collective lines were located outside the barn, approximately 1 m from side screens and 1 m below the barn roof gutters (Fig. 3).

### 2.4. Climate and side screen opening

Temperature and relative humidity were continuously measured inside and outside the barn using combined sensors (Rotronic Instrument Corp., Hauppauge NY, USA; Fig. 3). Hourly mean values were stored in a data-logging system (CR1000, Campbell Scientific, Inc., Logan, UT, USA). Outside wind speed and direction data were derived from the nearest meteorological station (KNMI, station De Bilt, at 10 m height and located 19 km from the measurement site) which was considered as representative of the local conditions in this flat area near sea level.

The opening percentage of both side wall screens was continuously monitored by a sensor (homemade based on a rotary multi-turn position sensor connected to the curtain axle giving a signal between 0 and 1V, ranging from fully closed to fully opened) and logged. When the daily mean signal was less than 0.25, the opening size of the side screens was “restricted” and the ventilation management called conventional, representing the ventilation situation of an ordinary dairy barn in the Netherlands where most of the air leaves the barn through the ridge; when the signal was more than 0.25, the side screens were considered to be “open” resulting in a very open ventilation where air may leave the barn both through the ridge and as a cross-flow through the side openings (Fig. 1). During the measurement periods, both side screens were open or closed in the same manner. Table 3 describes animal and climate characteristics (temperature, relative humidity and wind) relative to periods when VR were measured and when side screens were either open or restricted.

### 2.5. Data processing and ventilation rate calculations

Due to instrument failure and revision, not all data between May 2012 and December 2013 was available (Table 3). The

<table>
<thead>
<tr>
<th>Side screens</th>
<th>Open</th>
<th>Restricted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement periods: Month (consecutive days)</td>
<td>June 2012 (11 d)</td>
<td>December 2012 (3 d)</td>
</tr>
<tr>
<td></td>
<td>July 2012 (3 d)</td>
<td>October 2013 (24 d)</td>
</tr>
<tr>
<td></td>
<td>August 2012 (4 d)</td>
<td>November 2013 (13 d)</td>
</tr>
<tr>
<td></td>
<td>November 2012 (9 d)</td>
<td>December 2013 (7 d)</td>
</tr>
<tr>
<td>Number of cows</td>
<td>190</td>
<td>188</td>
</tr>
<tr>
<td></td>
<td>196</td>
<td>194</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>199</td>
</tr>
<tr>
<td>Milk production (kg d⁻¹ cow⁻¹)</td>
<td>27.6</td>
<td>25.8</td>
</tr>
<tr>
<td></td>
<td>29.4</td>
<td>27.2</td>
</tr>
<tr>
<td></td>
<td>30.8</td>
<td>30.6</td>
</tr>
<tr>
<td>Live weight adult cows (kg)</td>
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<td>25.3</td>
</tr>
<tr>
<td></td>
<td>660</td>
<td>673</td>
</tr>
<tr>
<td></td>
<td>670</td>
<td>685</td>
</tr>
<tr>
<td>Temperature barn (°C)</td>
<td>5.3</td>
<td>4.2</td>
</tr>
<tr>
<td></td>
<td>14.7</td>
<td>15.5</td>
</tr>
<tr>
<td></td>
<td>23.4</td>
<td>27.1</td>
</tr>
<tr>
<td>Temperature outside (°C)</td>
<td>2.2</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>12.9</td>
<td>9.6</td>
</tr>
<tr>
<td></td>
<td>22.1</td>
<td>16.9</td>
</tr>
<tr>
<td>Delta Temp. (barn – out, °C)</td>
<td>0.73</td>
<td>0.54</td>
</tr>
<tr>
<td></td>
<td>1.84</td>
<td>5.90</td>
</tr>
<tr>
<td></td>
<td>3.91</td>
<td>12.24</td>
</tr>
<tr>
<td>Relative humidity barn (%)</td>
<td>70.6</td>
<td>82.7</td>
</tr>
<tr>
<td></td>
<td>88.8</td>
<td>95.4</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>100</td>
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<tr>
<td>Relative Humidity outside (%)</td>
<td>64.3</td>
<td>76.3</td>
</tr>
<tr>
<td></td>
<td>80.0</td>
<td>88.4</td>
</tr>
<tr>
<td></td>
<td>98.5</td>
<td>99.6</td>
</tr>
<tr>
<td>Wind speed (m s⁻¹)</td>
<td>1.75</td>
<td>1.33</td>
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<td></td>
<td>3.55</td>
<td>3.88</td>
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<tr>
<td></td>
<td>6.54</td>
<td>8.50</td>
</tr>
<tr>
<td>Wind direction (°)</td>
<td>118</td>
<td>126</td>
</tr>
<tr>
<td></td>
<td>210</td>
<td>202</td>
</tr>
<tr>
<td></td>
<td>324</td>
<td>280</td>
</tr>
</tbody>
</table>
dataset was further filtered to consider only days where at least 19 out of 24 h of data were available for the calculation of ventilation rates (i.e. 80% of hourly measurements, a criterion derived from the VERA test protocol for Livestock Housing and Management Systems, 2011).

Ventilation rate calculations were performed on an hourly basis using either the naturally emitted (CO₂) or the artificially injected (SF₆) tracer gas. Previous and related work indicated that the influence of mean integration time (5, 15, 30 and 60 min) on concentrations was negligible (Mendes, 2014). Ventilation rates were reported on a daily basis in order to integrate intra-day variations due to climate parameters and/or cow activity patterns (Pedersen & Sällvik, 2002).

2.5.1. Natural tracer gas (CO₂)

The amount of CO₂ produced (and emitted) by the animals acted here as the tracer gas. Ventilation rate (VR₉μ) based on this tracer method was calculated by the following equation:

$$VR_{CO_2} = \frac{PCO_2}{N_{animals}}$$

where VR₉μ is expressed in m³ h⁻¹ animal⁻¹; PCO₂ is the amount of CO₂ produced (in m³ h⁻¹) at the barn level; [CO₂]barn represents the barn concentration (in m³ m⁻³), derived from spatial sampling options provided by the measurement points at the central axis and the ridge line (for ease of presentation and clarity, the specific spatial sampling strategies applied for determining [CO₂]barn, are described in the results section); [CO₂]outside represents the outside CO₂ concentration (in m³ m⁻³); Nanimals is the number of animals present in the barn.

PCO₂ was calculated using the CIGR equations provided by Pedersen and Sällvik (2002). The method is based on the calculation of total heat production (in W) by the animals (from maintenance, milk production and pregnancy) at "normal" indoor temperature of 20 °C. A coefficient is then applied (0.20 m³ h⁻¹ hpu⁻¹; hpu = heat production unit = 1000 W at 20 °C; Pedersen et al., 2008) to estimate the amount of CO₂ produced in m³ h⁻¹ at barn level (PCO₂). The factor 0.20 takes into account a small constant percentage of emissions from the manure (Pedersen et al., 2008). The estimated CO₂ production from the CIGR equations are representative for the mean daily CO₂ production (no diurnal effects included), but are expressed on an hourly basis.

This procedure can be described by the following equations:

$$PCO_2(dairy\ cow) = \frac{0.2 \times (5.6m^{0.75} + 22 \times Y_1 + 1.6 \times 10^{-5} \times p^1)}{1000}$$

$$PCO_2(dry\ cow) = \frac{0.2 \times (5.6m^{0.75} + 1.6 \times 10^{-5} \times p^1)}{1000}$$

$$PCO_2(heifer) = \frac{0.2 \times (7.64m^{0.69} + Y_2 \times \frac{M}{100} - 1 \times \frac{Y_2 \times 0.10m^{0.5}}{1 + e^{1.9Y_2}} + 1.6 \times 10^{-5} \times p^1)}{1000}$$

where m is the average weight of the animals (kg); Y₁ is the cow daily milk production (kg d⁻¹); p is the cow pregnancy state (d); M is the energy content of feed (MJ kg dry matter⁻¹); Y₂ is the heifer daily gain (kg d⁻¹).

When information was not available, the following constant values were used (Pedersen & Sällvik, 2002): m was set to 500 kg for heifers; M was fixed at 10 MJ kg dry matter⁻¹; Y₂ was 0.6 kg d⁻¹; dairy and dry cows were considered to be 160 d of pregnancy and heifers 140 d of pregnancy (Smits, personal communication).

The total CO₂ production in the barn (PCO₂tot, m³ h⁻¹) was determined every day as:

$$PCO_2^{tot} = PCO_2(dairy\ cow) \times number\ of\ dairy\ cows$$

$$+ PCO_2(dry\ cow) \times number\ of\ dry\ cows + PCO_2(heifer) \times number\ of\ heifers$$

Finally, PCO₂tot was corrected for barn temperature (tbarn, °C) as deviations from the standard condition of 20 °C that is assumed for estimating heat production, according to Pedersen and Sällvik (2002):

$$PCO_2 = \frac{PCO_2^{tot} \times (1000 + 4 \times (20 - tbarn))}{1000}$$

2.5.2. Artificial tracer gas (SF₆)

In the constant tracer gas injection technique, the barn is initially charged with tracer gas and then the injection rate is set to a constant value that produces a measurable concentration within the detection range of the measuring equipment. In this method it is necessary to precisely control the injection rate at a known rate and measure the tracer gas concentration in the barn. As with the method adopted for CO₂, SF₆ barn concentrations were measured using a variety of sampling options (Fig. 3). The barn ventilation rate (VR₆₆₆), expressed in m³ h⁻¹, was determined by the injection rate (l, in m³ h⁻¹) and the concentration (C, in m³ m⁻³) of the tracer gas in the building envelope (derived from Demmers et al. 2001), assuming perfect mixing, negligible concentrations of the tracer gas inside and outside the barn before the gas is injected, and steady-state conditions. The resulting ventilation rate calculated at building level is then divided by the number of animals present (Nanimals).

$$VR_{SF_6} = \frac{l}{N_{animals}}$$

2.6. Codification and statistical analyses

To compare ventilation rates estimated using either SF₆ (VR₆₆₆) or CO₂ (VR₉μ) as tracers, the daily ratios between both methods (VR₉μ/VR₆₆₆) were calculated for the days when both methods could be applied (see Table 3). For VR₉μ, a distinction was made according to the equipment...
used for the measurement of CO₂ concentrations: \( \text{VR}_{\text{CO₂,NDIR}}; \text{VR}_{\text{CO₂,Laser}}; \text{VR}_{\text{CO₂,PAS}} \). VR ratios were then compared between measurement strategies (number of measurement points or ventilation situation) using means, minimum and maximum, and also coefficient of variation (CV) as an indicator of the variability.

Grubbs’ tests (maximum normed residual test) were used to detect outliers (2 ratios were removed from the dataset corresponding to abnormal \( \text{VR}_{\text{CO₂}} \) above 15,000 m³ h⁻¹ animal⁻¹⁻¹).

\( \text{VR}_{\text{CO₂}}/\text{VR}_{\text{SF₆}} \) ratios were compared to the theoretical value of 1 using Student’s t-tests (Minitab 17, Minitab, State College, Pennsylvania, USA). To determine the influence of the “horizontal” sampling strategy (number of points considered for concentration measurements, only for restricted ventilation situations) or of the ventilation strategy (side screens restricted or open) for a given “horizontal” sampling strategy (based on the previous analysis), one-way analyses of variance (one-way ANOVA, Minitab 17) were performed following the statistical models below:

\[
Y_i = \mu + \text{NbPoints}_i + \epsilon_i
\]

\[
Y_i = \mu + \text{VentilStrategy}_i + \epsilon_i
\]

where \( Y \) is the studied variable (VR ratio), \( \mu \) is the average, \( \text{NbPoints} \) is the number of points considered for concentration measurements using NDIR sensors (1 vs. 2, vs. 3, vs. 5 individual sampling points; 3 df), \( \text{VentilStrategy} \) is the ventilation strategy (side screens restricted or open; 1 df); and \( \epsilon \) is the error associated with each \( Y_i \). Pairwise test comparison between every level of sampling (1 vs. 2, vs. 3, vs. 5 individual sampling points) or ventilation (open vs. restricted) strategies was also realised with p-values adjusted with Tukey–Kramer corrections. One-way ANOVA was only performed for intra-equipment comparisons of CO₂ concentrations. This is the reason why the “vertical” sampling strategy was not tested (CO₂ monitored with NDIR sensors or OP laser in the central axis vs. PAS in the ridge). Normality of the residuals was checked visually.

3. Results and discussion

3.1. Some constraints in the calculation of \( \text{VR}_{\text{CO₂}} \)

This study compared ventilation rates estimated using either CO₂ or SF₆ as tracers and different sampling strategies for gas concentration measurements. One particular aspect of this study was that CO₂ concentrations were measured using NDIR sensors, a PAS or an OP-laser depending on the sampling location (Table 1). Mendes, Ogink, et al. (2015) showed that the NDIR sensors measured systematically higher CO₂ concentrations in the barn (average + 13%) compared with the PAS analyser. They consequently advised users of NDIR sensors to use the same equipment for background measurement, thereby eliminating the bias in the background corrected CO₂ concentrations. Here, some sensors were placed outside the barn to measure background concentrations but they did not produce reliable results and their records could not be used. The sensors appeared to be positioned too close to the outlets, and as such were occasionally subject to direct effects of outgoing barn air, thus overestimating background concentrations. Bias was also observed in outside CO₂ concentrations measured with the PAS analyser, and they also could not be used for same reasons. Zhang et al. (2010) determined that deviations were limited if a fixed value was estimated from outdoor measurements and was used for the inlet gas concentrations. It was therefore decided to use a constant value of 417 ppm for background CO₂ concentration based on outdoor measurements around dairy barns (CV between daily means, 8%), from previous experiments in similar conditions (Mosquera, Smits, & Ogink, in prep.). The value of 417 ppm was, however, obtained using a PAS analyser. This probably resulted in higher CO₂ concentration gradients than would have been calculated using NDIR sensors placed indoors and outdoors, thus lowering the resulting \( \text{VR}_{\text{CO₂,NDIR}} \). The use of this constant value could lead to higher variability in the estimation of \( \text{VR}_{\text{CO₂,PAS}} \) and \( \text{VR}_{\text{CO₂,Laser}} \) compared with direct measurements of background concentration.

3.2. Spatial sampling strategies

Considering only restricted ventilation situations representing conventional ventilation management, air flow rate estimates, based on either using CO₂ or SF₆ as a tracer, were compared using different spatial sampling strategies.

3.2.1. Horizontal sampling strategy

To study the influence of the use of one or more sampling points and their horizontal distribution, ventilation rate ratios (\( \text{VR}_{\text{CO₂}}/\text{VR}_{\text{SF₆}} \)) were calculated from different series of measurement points, comparing concentration measurements obtained from one (n = 3 in the central axis), two (n = 2 and 4), three (n = 1, 3 and 5) or all 5 individual sampling points in the central axis (Fig. 3). At this spatial resolution (individual points), only \( \text{VR}_{\text{CO₂,NDIR}} \) could be used (Table 1). Depending on the number of considered sampling points, mean \( \text{VR}_{\text{CO₂,NDIR}}/\text{VR}_{\text{SF₆}} \) ratios varied between 0.52 and 0.70 (Table 4). This indicates that ventilation rates calculated with CO₂ as a tracer were on average between 50 and 30% lower than when SF₆ was used. As mentioned in Section 3.1, this difference could partly be related to the combined use of NDIR sensors and background measurement based on the PAS analyser. The use of a corrected CO₂ background concentration of 471 ppm (to take into account the 13% mean higher estimation of CO₂ concentrations by NDIR sensors estimated in Mendes, Ogink, et al., 2015) indeed leads to \( \text{VR}_{\text{CO₂}} \) being increased by 30% (±33%).

Ventilation rate estimates have been shown to be highly dependent on the measurement position (Ikeguchi & Hideki, 2010). Some authors judged that the best position for tracer gas sampling was the outlet and that neither a single point nor the mean of the entire barn are representative of the outlet concentration (Van Buggenhout et al., 2009; Wu et al., 2012). However, in naturally ventilated barns, outlets can also act as inlets depending on wind direction, leading to large errors in the calculation of ventilation rates (Bjerg et al., 2012; Van Buggenhout et al., 2009; Wu et al., 2012). Using an optimisation procedure with different simulated barn sidewalls opening situations, Shen et al. (2012) determined that the universal
optimal sampling position was close to the centre of the barn (i.e. near the central axis, at 27% of the barn height). This recommended sampling position corresponds to measurements just above the animal occupied zone (AOZ) and is in agreement with conclusions of Mendes, Edouard et al. (2015). On the basis of this information, five sampling points, evenly distributed along the central axis at approximately $H = 3.0$ m (i.e. 27% of the barn height), were chosen. When measurements are made frequently over long periods, Ngwabie et al. (2009) showed that a good choice of single sampling locations may give satisfactory results. Using one single point in the centre of the barn was therefore investigated and compared to estimates of ventilation rate using the mean of 2, 3 or 5 points. The ratio calculated using concentrations measured at one location (sampling point n; Fig. 3) was significantly lower than the ratios using measurements from 3 or 5 locations ($P < 0.01$, RMSE = 0.21). $VR_{CO_2}$ was quite similar whatever the individual point considered since $SF_6$ was evenly distributed across the barn. This lower ratio was therefore related to a lower $VR_{CO_2}$ calculated at point n'3 because of the higher $CO_2$ concentration measured due to the presence of dairy cows at this location. Using only one sampling point, though it was located in the middle of the barn, led to highly variable ventilation rates being calculated (CV of ratios = 41%; Table 4) especially when using $CO_2$ as a tracer. This suggests that this point was not very representative of gaseous concentrations inside the whole of the building. As previously discussed by Mendes, Ogink, et al. (2015), gaseous concentrations can vary widely inside the barn depending on multiple factors, including barn geometry, occupation and wind flow patterns as well as inter-sensor variability; the use of several sampling locations should therefore be favoured to represent the average concentration of the barn. The mean ratio of ventilation rates was the highest using the average of 5 points ($0.70 \pm 0.03$) and it gave the lowest coefficient of variation (25% see Table 4). This result shows that to calculate the accurate ventilation rate for the barn using an average concentration derived from multiple sample points along the barn length is preferred to using single points. The placement of these sampling points should be carefully chosen to represent the spatial variability of target gases concentrations and this depends on the barn layout.

3.2.2. Vertical sampling strategy

Gas concentrations were recorded both along the central axis ($H = 3$ m) and near the ridge of the barn. Depending on the sampling location, $CO_2$ concentrations were measured using NDIR sensors, OP laser or PAS (Table 1). Vertical effects, under restricted ventilation conditions, were studied by comparing VR ratios based on the available types of concentration measurements that encompassed the total barn length, hence in case of multiple measurement points (in the central axis) the averaged concentrations of all 5 individual measurement points were used.

Along the central axis of the barn, the mean VR ratio based on NDIR measurements for $CO_2$ concentration was lower ($0.70 \pm 0.03$) than that when the OP laser was used ($0.90 \pm 0.05$ see Table 5). From the higher VR values measured here by this type of NDIR sensors, both in comparison to the OP laser and to the PAS analyser (Mendes, Ogink et al., 2015), it can be inferred that the NDIR sensors overestimate $CO_2$ concentrations. In the ridge, using the PAS for $CO_2$ concentration measurements, the VR ratio of $0.89 \pm 0.05$ was very similar to that determined at the central axis using the OP laser. In both cases, ratios were close to 1, yet they were statistically different ($P = 0.05$ and 0.04 respectively using OP laser and PAS). Along the central axis of the barn, the coefficient of variation was however greater than that at the ridge (central axis with OP laser: $CV = 35\%$, minimum ratio = $0.40$, maximum ratio = $1.81$; ridge with PAS: $CV = 16\%$, minimum ratio = $0.74$, maximum ratio = $1.19$). This lower variability of ratios in the ridge indicates that measuring at this location could result in more precise estimated values for ventilation rate. This result is not consistent with the optimal position for concentration measurements defined by Shen et al. (2012) using response surface methodology. The major difference between their study and ours is that the ridge did not act as an outlet in the study of Shen et al. (2012). When the ridge functions as a permanent outlet, it may yield more precise estimates of the VR ratios because concentrations of both $CO_2$ and $SF_6$ are more stable and are similar to the conditions that occur near the outlets of mechanically ventilated livestock barns. However, measurements made at the central axis of the barn took place at $H = 3.0$ m which is relatively close to the AOZ. The AOZ is known as a region of relatively high turbulence, where the naturally produced, or artificially injected gases, are likely to be mixed with fresh air, causing the concentration measurements to be more variable. The increased variability of gaseous concentrations of $CO_2$ and $SF_6$ as the sampling location approaches to the AOZ ($H = 4$ to $1$ m) in this dairy cattle barn was also observed by Mendes, Edouard, et al.

### Table 4 - Ratios of ventilation rates calculated using $CO_2$ (monitored with NDIR sensors) or $SF_6$ as a tracer gas ($VR_{CO_2/NDIR}$ / $VR_{SF_6}$, dimensionless) when inlet side screens were restricted; days of measurement (N), mean, standard error of the mean (SEM), minimum, maximum and coefficient of variation (CV, %) for each spatial sampling strategy (sampling points) in the central axis and results from the variance analysis.

<table>
<thead>
<tr>
<th>Sampling point(s)</th>
<th>N</th>
<th>$VR_{CO_2/NDIR}$ / $VR_{SF_6}$ (dimensionless)</th>
<th>CV (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>SEM</td>
</tr>
<tr>
<td>Point 3</td>
<td>46</td>
<td>0.52</td>
<td>0.03</td>
</tr>
<tr>
<td>Points 2 and 4</td>
<td>40</td>
<td>0.63</td>
<td>0.03</td>
</tr>
<tr>
<td>Points 1, 3 and 5</td>
<td>45</td>
<td>0.69</td>
<td>0.04</td>
</tr>
<tr>
<td>5 points</td>
<td>38</td>
<td>0.70</td>
<td>0.03</td>
</tr>
</tbody>
</table>

* Different numbers of N result from missing data for individual NDIR sensors at some days.
* Different letters refer to significant differences ($p < 0.05$) from the ANOVA.
Ratios of ventilation rates calculated using CO2 as a tracer gas (or SF6 concentrations (average of the barn length) and for being on the average 3.3 difference (Table 3). Outside temperatures differed slightly, restricted situations and therefore unlikely to explain the speeds and directions were very similar for open and average, higher than when side screens were restricted. Wind temperatures of almost 6 with a mean difference between inside and outside temper-

are difficult to dissociate from variations in side screen variations in temperature that complicates the interpretation. For example, in Wang et al. (2016) a lower VR was recorded for a lower outdoor temperature with fully closed curtains compared to higher temperature with fully open curtains. In our study, turbulence might also have affected the measurement of concentrations at 3–4 m above the floor with very open situations preventing proper mixing of air. Also, cows can introduce resistance in the AOZ leading to difficulties to analyse air flow patterns (Wu et al., 2012). Cross ventilation in very open situations can also affect gas mixing behaviour (Demmers et al., 1998). However, in the ridge the mean VR ratios for open and conventional ventilations were very similar (0.88 vs. 0.89, P = 0.92; Table 5). In this case, the variability of the ratios doubled when the side screens were open compared with conventional ventilation (CV = 32% vs. 16%).

Regardless of the location or type of instrument used to measure CO2 concentration, average VRCO2 were always lower than VRSF, (i.e. mean ratios < 1). This result is quite normal in the literature but it is very difficult to conclude whether one method overestimates or the other underestimates ventilation rates (Kiwan et al., 2013; Muller et al., 2007; Zhang et al., 2005). Arguments exist for both hypotheses and these are discussed in the following sections.

3.3. Conventional versus very open ventilation situations

To analyse the impact of opening the barn side screens, which results in air leaving the building both by the ridge and through the sides of the barn, the ratios found in conventional and very open ventilation situations were compared using available CO2 and SF6 measurement options that represented the total barn length. VR ratios were plotted against either VRCO2 or VRSF, in both ventilation situations to illustrate both the trends and dispersion in the data (Fig. 4).

Along the central axis of the barn, the mean VR ratio was lower for very open situations compared with conventional ones (0.61 vs. 0.70 using NDIR sensors, P = 0.06; Table 5). When the side screens were open, both VRCO2 and VRSF were, on average, higher than when side screens were restricted. Wind speeds and directions were very similar for open and restricted situations and therefore unlikely to explain the difference (Table 3). Outside temperatures differed slightly, being on the average 3.3 °C lower for the restricted situation with a mean difference between inside and outside temperatures of almost 6 °C (Table 3). As reported in the literature, this can lead to lower ventilation rates and could partly explain the differences observed in the present study (e.g. Kiwan et al., 2013; Ngwabie et al., 2011; Wang et al., 2016). However, in most of these studies, variations in temperature are difficult to dissociate from variations in side screen opening rates which complicates the interpretation.

### Table 5 - Ratios of ventilation rates calculated using CO2 or SF6 as a tracer gas (VRCO2/VRSF, dimensionless; days of measurement (N), mean, standard error of the mean (SEM), minimum, maximum and coefficient of variation (CV, %) for each sampling site, each equipment used for the measurement of CO2 concentrations (average of the barn length) and for restricted or open side screens.

<table>
<thead>
<tr>
<th>Sampling site</th>
<th>Equipment for CO2 measurement</th>
<th>Side screens</th>
<th>N</th>
<th>VRCO2/VRSF (dimensionless)</th>
<th>P value&lt;sup&gt;d&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NDIR sensors</td>
<td>Restricted</td>
<td>38</td>
<td>0.70*** 0.03 0.37 1.04 25</td>
<td>0.06</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Open</td>
<td>19</td>
<td>0.61*** 0.03 0.37 0.80 20</td>
<td></td>
</tr>
<tr>
<td>Ridge</td>
<td>OP Laser</td>
<td>Restricted</td>
<td>43</td>
<td>0.90* 0.05 0.40 1.81 35</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Open</td>
<td>10</td>
<td>0.89* 0.05 0.74 1.19 16</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PAS</td>
<td>Restricted</td>
<td>8</td>
<td>0.88 0.10 0.51 1.37 32</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Open</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup> [SF6] was always measured using the gas chromatograph.

<sup>b</sup> Different numbers of N result from missing data for some gas measurement devices at some days.

<sup>c</sup> Mean significantly different from 1 (* p < 0.05, ** p < 0.01, *** p < 0.001; t-test).

<sup>d</sup> Refers to the p value from the ANOVA comparing restricted and open situations intra-equipment for CO2 concentration measurement.
deep litter, the contribution of manure to the total CO₂ production at the house level might be higher (Pedersen et al., 2008). Liquid manure stored in the pit beneath the slatted floor has been reported to contribute up to 37.5% of the total CO₂ release from a fattening pig house (Ni, Vinckier, Hendriks, & Coenegrachts, 1999). This value might appear to be extreme; however, it suggests that the quantity of CO₂ release from manure could be seriously underestimated in the CIGR equations. Similarly, Edouard et al. (2012) showed that the CO₂ production from dairy cattle bedding (i.e. deep litter) was close (80%) to that from the animals themselves. In the barn considered in the present study, the pit below the slats was only emptied a few times a year (even not emptied at all between 15th of August and 31st of January following national rules on manure field application) and the building included a small area of deep litter for calving. When performing calculations for PCO₂ by progressively increasing the percentage of manure contribution, i.e. by increasing the coefficient from 0.20 to 0.22 or 0.24 m³ h⁻¹ hpu⁻¹ respectively by considering a contribution from manure of 18 or 25% of the total CO₂ production, the resulting VRCO₂ increased by 10% or 20% respectively compared to the use of the 0.20 coefficient. This is far from being negligible. More empirical research is needed to better refine estimates of the contribution of manure to total barn CO₂ concentration. Its ease of use in cattle barns however lead many authors to favour this method, especially in experiments to determine emission factors where random errors in single daily measurement values play a minor role in the overall accuracy of the emission factor (Ogink et al., 2013). Looking at the positive linear trends between ratios and VRCO₂ (Fig. 4), it can be hypothesised that VRCO₂ values are more sensitive to changes in VR than are VRSF₆.

### 3.3.2. Hypothesis: the SF₆ mass balance overestimates VRSF₆

The use of tracer gas for the estimation of ventilation rates assumes complete mixing of the tracer with air inside the building. However, the air inside naturally ventilated livestock buildings is known to be far from completely mixed (Demmers et al., 1998). It has been shown here that in very open situations, both VRCO₂ and VRSF₆ were on the average higher than under conventional ventilation conditions and their ratio more variable. Examining the greater dispersion of the data with VRSF₆ (Fig. 4), it seems that the SF₆-based method had poorer precision when used to estimated ventilation rates compared to the CO₂-based method. In open situations, ventilation rates estimates based on tracer techniques are subject to large variations depending on climatic conditions, especially wind speed and direction. The accuracy of the tracer method was indeed shown to be lowest at high wind speed compared to calm days (Demmers et al., 1998). This incomplete mixing of ventilated air and ingoing air may lead to lower tracer gas concentration at the sample location, resulting in an overestimation of the ventilation rate (Ogink et al., 2013). Although large numbers of injection points for

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**Fig. 4** – Plots of VRCO₂/VRSF₆ ratios against VRCO₂ (with CO₂ concentrations measured either using PAS or laser) and VRSF₆ measured along the central axis of the barn (A) and in the ridge (B) for “restricted” ventilation situations (full symbols) and “open” ventilation situations (open symbols).
SF₆ were used, its release might not be that well integrated with air close to the emitting surface of pollutant gas as CO₂ released from animals. The possibility that SF₆ was not injected at the same and constant rate at all the injection points during the whole measurement period (e.g. because of outlets blocked with dust), leading to a heterogeneous distribution of SF₆ concentrations in the barn cannot be excluded. Particularly in the case of strong cross ventilation, insufficient mixing of the SF₆ molecules in the entire barn, with a high molecular weight, might create conditions where the SF₆ molecules do not reach the heights of the measurement points when passing the side outlets. Missing a small fraction of the SF₆ injected in the barn might have resulted in higher VR₆. This technical reason, and the costs of SF₆ equipment, can be seen as constraints for the use of this method in large scale experiments for the determination of emission factors.

4. Conclusion

- Measuring the average tracer concentration over a full barn length leads to more accurate ventilation rates than using one single point, even if it is placed in the middle of the barn.
- For conventional ventilation situations, when technically feasible, measurements in the ridge should be favoured. Measured concentrations are likely to be less influenced by turbulence and more representative of the barn average. Concentration measurements along the central axis of the barn may provide suitable results although larger variability due to spatial variations in concentration may occur. This may be a helpful sampling strategy provided other gas and/or dust measurements are made at the same locations.
- In very open situations, both VRₐ and VR₆ were on average higher than in conventional ventilation. Higher variability of VR ratios indicated that cross ventilation might lead to disturbed air flows and affect gas mixing behaviour.
- Regardless of the sampling location, and the equipment used for CO₂ concentration measurements, VRₐ were, on average, lower than VR₆ (ratios < 1). This can be related to a systematic overestimation of CO₂ concentration through an indication of bias in NDIR sensors, an underestimation of CO₂ produced by the manure at the barn level, and/or overestimation of VR₆ due to incomplete mixing of air.
- The NDIR method led to lower average VR ratios as compared to the other two methods for the measurement of CO₂ concentrations, suggesting a systematic overestimation of CO₂ concentrations. However, it also yielded to the lowest values for CVs (both in conventional and very open conditions). It is recommended that these sensors are used with great care with CO₂ concentrations corrected with background measurements using the same type of sensors.
- Excluding the use of NDIR sensors, this study showed that both independent methods for the estimation of ventilation rates, gave very similar results with a small systematic difference, being 10–12% lower in the CO₂ mass balance method compared to SF₆ based measurements. This difference might be attributed to potential bias in both methods.

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