Tracer gas technique, air velocity measurement and natural ventilation method for estimating ventilation rates through naturally ventilated barns

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Abstract: Naturally ventilated barns have the advantage of providing an energy-efficient and low-noise micro-environment for animals. Such barns are very common, especially for cattle, which are a major source of ammonia and methane emissions as well as other airborne pollutants. Emission fluxes are calculated as the product of the ventilation rate (VR) and the gas concentration. The VR of naturally ventilated barns are directly influenced by atmospheric conditions. Therefore, the estimation of VR involves high uncertainties; furthermore, there is no reference method for VR estimation. For these reasons, three different methods were investigated to estimate VR through naturally ventilated dairy barns: (1) the tracer gas technique, using radioactive isotope Krypton-85 (^{85}Kr), (2) the measurement of the air velocity through the barn openings, and (3) the natural ventilation method. The investigations were performed in two naturally ventilated dairy barns (each with a volume of 5,670 m^3) during mild ($T \geq 17^\circ C$) and cold weather ($T < 17^\circ C$) conditions. The VR ranged between 48,000 and 475,000 m^3/h. There was a significant ($p<0.01$) correlation between all three methods for barn A (Pearson's correlation coefficient 0.59-0.86). For barn B only, the tracer gas and the natural ventilation method showed a significant ($p=0.03$) correlation (Pearson's correlation coefficient 0.62). The season (mild or cold) and the VR estimation method both had a significant ($p<0.03$) effect on the estimated VR for both barns. The outside wind speed had a significant ($p<0.005$) effect on the estimated VR for barn A. For barn B, this effect was not significant ($p=0.052$). The tracer gas technique used has the advantage of measuring the tracer with high resolution in time (1 Hz) and space (18 or more measured points).

Keywords: Natural ventilation, tracer gas technique, radioactive isotope ^{85}Kr, air velocity, air exchange rate, dairy barn

1 Introduction

The structure of livestock barns and the types of

ventilation systems used have substantial influence on the indoor climate of the barn, which in turn affects animal welfare and the airborne gas emission rate (Hellickson and Walker, 1983). Ventilation is required for removing harmful gases to ensure indoor air quality and to meet the demands of both animals and humans (Seedorf et al., 1998). The microclimatic conditions, such as the concentration of gases, air velocity, dust, air temperature, and relative humidity, influence animal welfare, workers and the structure of the barn and the barns components (Hartung and Schulz, 2011; Radon et al., 2002). Air

flow patterns in naturally ventilated barns are mainly influenced by the natural driving forces of wind effect and thermal buoyancy. However, the requirements of the animals have to be fulfilled at any given time. The minimum VR per cow is 100 m^3/h to maintain the CO_2 concentrations below the recommended harmful limits of 3,000 ppm (CIGR, 1984). For a typical dairy barn with 100 m^3 space per cow, the resulting minimum air exchange rate to fulfill this requirement of refreshment is approximately once per hour. The air velocity needed across the cattle ranges between 1 and 2 m/s (Turner, Warner, and Chastain, 1997). The estimation of VRs throughout such barns is essential for determining indoor air quality and for estimating the emission flow rate of harmful gases, odor and particulate matters (Pedersen et al., 2004). Consequently, the estimation of emission flow rate is required to determine the minimum distances between livestock facilities and residential areas (Keck et al., 2010; Keck et al., 2011). The VR and gas concentration in the exhaust air must be known to quantify the emission flow rate. While the quantification of the emission flow rate from barns with forced ventilation is assessed by using a standard procedure, it is considered to be a challenge to estimate this flow from naturally ventilated barns. Naturally ventilated bars have wide air openings providing large contact surfaces with the outdoor environment; naturally ventilated barns are common in dairy farms (Berg et al., 2010; Müller, Möller, and Gläser, 2000; Müller, Rom, and Pedersen, 2006; Schrade et al., 2012). For naturally ventilated barns, the emission flow rates of the various gases are directly influenced by a number of factors, including atmospheric conditions that are constantly changing (Brehme, 2000). The VR throughout a naturally ventilated barn depends on both thermal buoyancy forces and wind pressure differences on the openings of the barn. There are several methods for determining the VR in such cases that are available in the literature, including the tracer gas technique. The tracer gas may be carbon dioxide (CO_2) (Kittas et al., 1996), radioactive isotope [85]Kr (Müller, and Möller, 1998), nitrous oxide (N_2O) or sulfur hexafluoride (SF_6) (Snell, Seipelt, and van den Weghe, 2003). Schrade (2009)

developed a new tracer ratio method with two tracer gases (SF_6 and trifluoromethyl sulfur pentafluoride (SF_5CF_3)).

Tracer gases are used for a wide variety of diagnostic techniques, including leak detection and atmospheric tracing (Liddament, 1996). In addition, the tracer gas technique is the only method of performing many types of quantitative measurements of ventilation. These include infiltration, air exchange measurements, fume hood efficiencies and the spreading of pollutants. In other cases, tracer gas analysis methods are preferred over other analysis methods because they are more convenient and more accurate (Peter et al., 1991). A very important aspect of the tracer gas technique is the possibility of testing occupied buildings. This is not only more convenient but also much more accurate because it takes into account the large effect that occupancy has on the VR (Liddament, 1996; Peter et al., 1991). Occupancy effects include, for instance, the effect of opening and closing doors and windows, which represent use under normal working conditions. Some tracer gases have also disadvantages. For example, [85]Kr is a radioactive isotope, and N_2O and SF_6 have Global Warming Potential (GWP) of 298 and 22,800 times the CO_2 GWP when compared over a 100-year period, respectively (IPCC, 2007). Generally, the VR of a building is usually estimated using one of the following tracer gas methods: (1) constant tracer gas injection; (2) variable tracer gas injection, and (3) concentration decay (Peter et al., 1991). Measurement data on tracer gas concentration, with its variability in time and in space, provides information on total and local VRs, ventilation effectiveness and the distribution of the gas inside the building (in this case, barns). This technique is based on the assumption of the complete mixing of tracer gas with air in the barn (Liddament, 1996). However, in practice, it is difficult to achieve uniform distribution and a thorough mixing of the tracer gas with indoor air in a naturally ventilated barn (Müller, and Möller, 1998; Samer et al., 2011a & 2011b). The concentration decay is the most convenient method for using [85]Kr in livestock barns. The reasons are many, including the large size of barns, environmental requirements, and costs. Additionally, the decay method

does not require a large amount of tracer gas.   A great deal of information about the spatial and temporal distribution of the air inside the barn can be estimated using an array of radiation counters that enable the measurement of [85]Kr impulses at different points with high resolution in time (one record per second).

2   Objectives

There is no accurate, reliable, online measurement method for estimating the VR throughout naturally ventilated barns.   Therefore, the purpose of this study is to compare the values of VRs estimated using three different methods: a tracer gas technique using [85]Kr, air velocity through the inlet openings and a natural ventilation method.   The comparison was performed using Pearson correlation analysis and an ANCOVA model.   This study contributes to a better understanding of the VR throughout naturally ventilated dairy barns.   This is accomplished using measurements of the air velocity through the inlet openings of the barn, the natural ventilation method (outside wind velocity and thermal buoyancy) and the tracer gas technique (concentration decay method).

3   Materials and methods

3.1   Experimental sites

The study consisted of several experiments conducted during both the mild (outside temperature ≥17℃, during April, September and October) and cold periods (outside temperature <17℃, during February, November and December) of the year in two dairy cattle barns located in northeast Germany.   Barn A was located at latitude of 51° 10' 43" N and a longitude of 12° 17' 37" E.   Barn B was located at latitude of 51° 6' 51.08" N and a longitude of 12° 14' 34" E.   The objective of this study was to determine the VRs throughout these dairy barns using the three aforementioned measurement methods.

Both experimental barns were naturally ventilated through adjustable openings using plastic curtains at the side walls.   The barns had the same dimensions and were very similar in construction.   The area of each barn was 1,575 m^2, with an internal space volume of 5,670 m^3, a length of 75 m, a width of 21 m and a height of 3.6 m. The housing system in both barns was a loose housing system with freestalls.   The milking center was in the building next door (see Figure 1 and Figure 3).
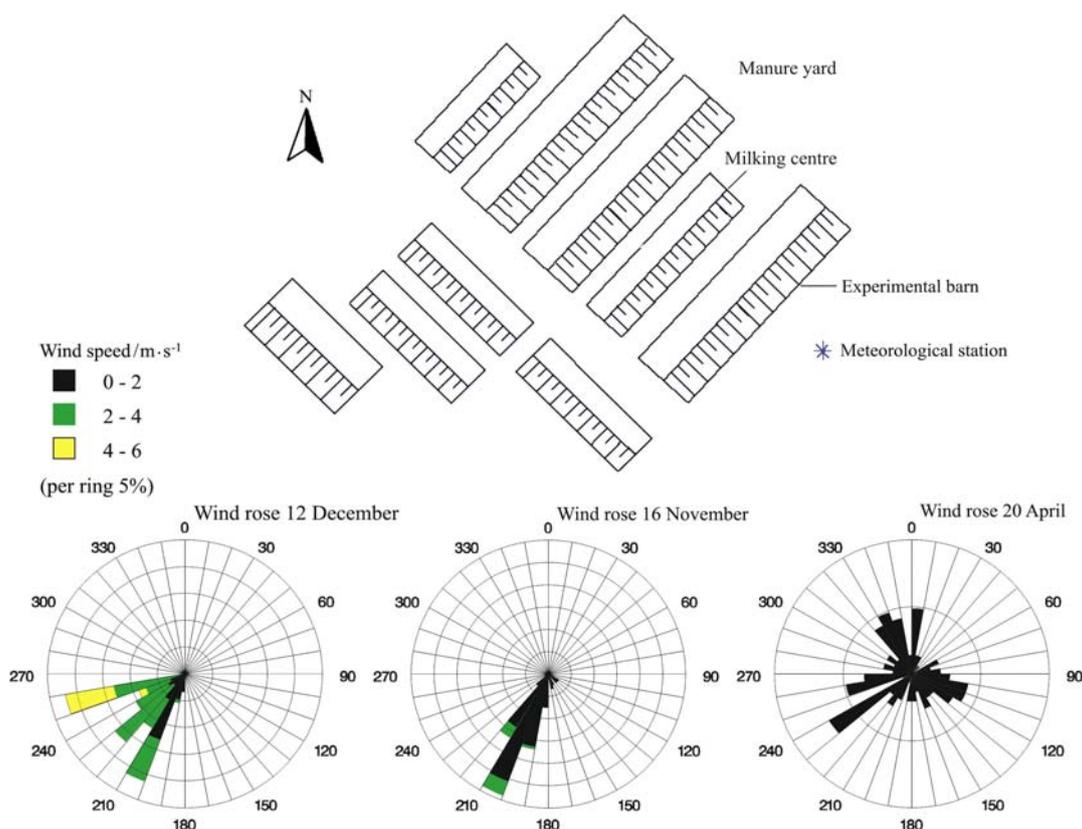

Figure 1   Site plan for barn A (Heidenreich et al., 2008) with wind roses for the measuring campaigns

Barn A had 230 freestalls with litter bedding and concrete floors with four rows of free-stalls, two feeding lines, and three manure alleys (Figure 2). The manure was removed every day by tractors and brought to the manure yard outside of the barn, where it was stored for several months. Inside the barn, there were five distributor fans over the manure alley to accelerate air movement along the barn's longitudinal axis. During all measurements, the fans were not in operation. Figure 1 shows the site plan of barn A, the nearby buildings (Heidenreich et al., 2008) and the wind roses for the measurement campaigns.
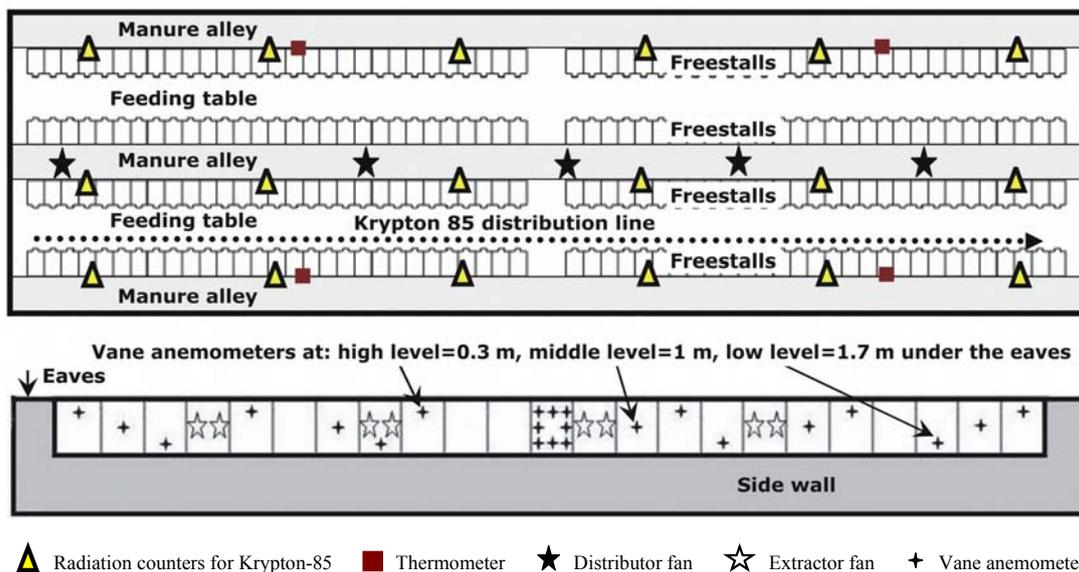

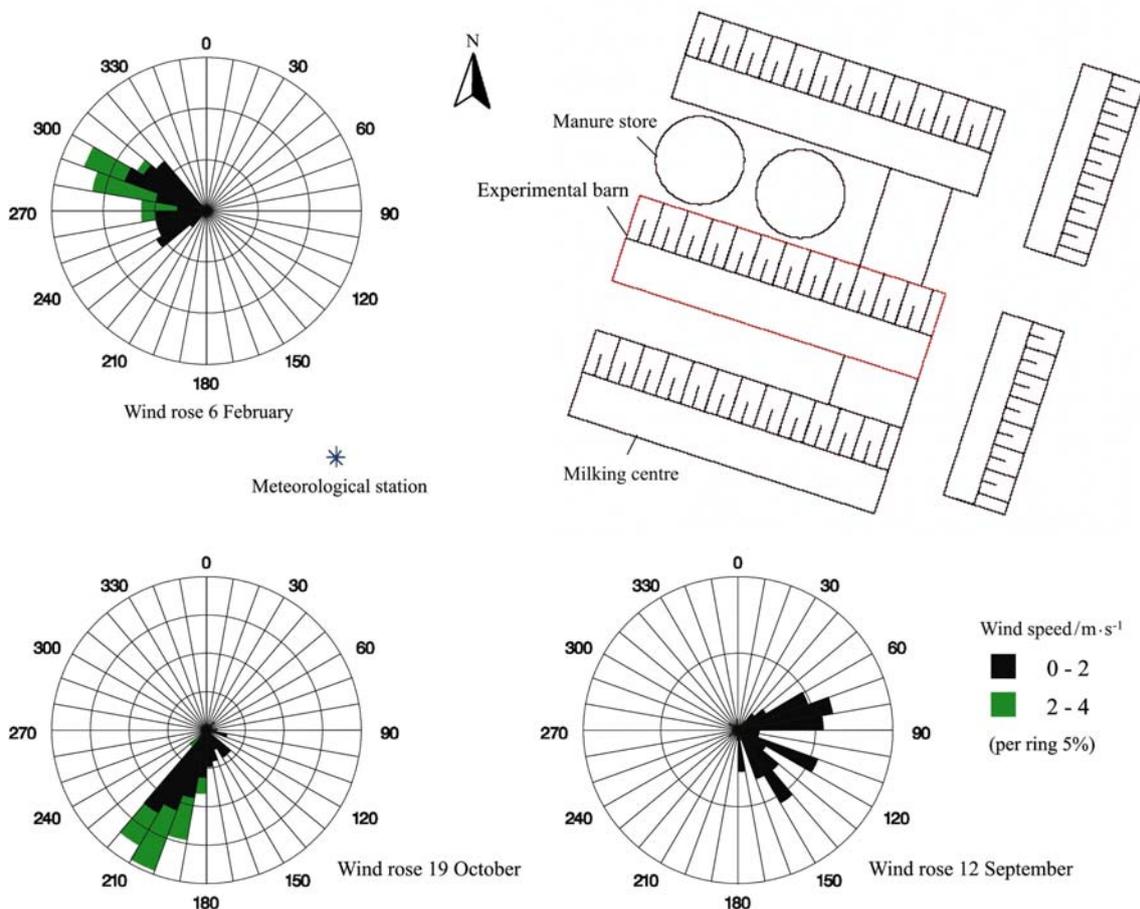Figure 2   Plan view (above) and side view (below) of barn A

Figure 3   Site plan for barn B (Heidenreich et al., 2008) with wind roses for the measuring campaigns

The barn was equipped with eight additional extractor fans at one side wall in the dominant wind direction (cross ventilation). The purpose of these side fans is to increase the VR and the air movement in the animal zone to avoid heat stress during hot summer conditions. The extractor fans were not in operation during the measurements such that the ventilation observed was in fact natural ventilation driven by outside wind velocity and thermal buoyancy. 24 vane anemometers were fixed along the same side wall in the direction of the prevailing wind to measure the horizontal air velocity through the openings, as shown in Figure 2.

Barn B had 240 freestalls with rubber mattresses. Close to the barn, to the north, there were two round manure tanks. Figure 3 shows the site plan of barn B (Heidenreich et al., 2008) and the wind roses for the measuring campaigns. The barn had concrete floors with four rows of freestalls and three manure alleys. Two rows of freestalls were placed at both side walls and the others two rows were face-to-face between the two manure alleys. Barn B has only one feeding table located between two manure alleys in the southern half of the barn (Figure 4). Four large distributor fans were located over the middle rows of laying boxes to enhance air movement along the longitudinal axis. The manure was removed by a manure v-scraper. The manure was stored in an underground concrete tank covered by iron sheets. Twenty vane anemometers were fixed along the side wall facing the prevailing wind direction (Figure 4), along with three more vane anemometers that were placed at the west gable wall of the barn.
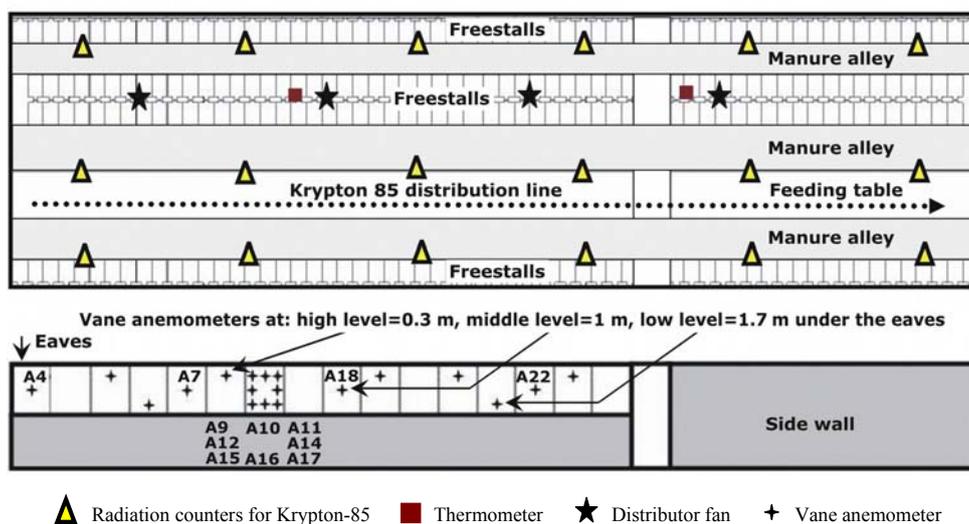

Figure 4   Plan view (above) and side view (below) of barn B

3.2   Tracer gas technique

The radiation counters, which detect the radioactive impulses of [85]Kr, were symmetrically distributed inside the barn at a height of 2 m above the floor. In fact, [85]Kr is a radioactive gas and it radiates gamma and beta rays. All twenty installed radiation counters (LB 6357, Berthold Technologies GmbH & Co. KG, Bad Wildbad, Germany) detected impulses with a frequency of 1 Hz. The tracer gas [85]Kr was injected into the barn along the feeding line, as described by Samer et al. (2011a), while the counters were measuring the resulting beta rays. The impulses represent the concentration of the radioactive gas over the time. The concentration of tracer gas was found to decay exponentially with time. By plotting the natural logarithm of tracer gas concentrations with time, a straight line should be obtained, where the gradient of the line is the air exchange rate in the barn. The VR can be calculated by multiplying the air exchange rate and the barn volume. Equation (1) explains the calculation of the air exchange rate:

$$N = \frac{\ln C(t_0) - \ln C(t_1)}{t_1} \qquad (1)$$

where, N is the air exchange rate (h[-1]); $C(t_0)$ is the concentration of tracer gas at time t_0; $C(t_1)$ is the gas concentration at time t_1, and t_1 is the total measurement

period (h).   The calculation of the air exchange rate is based on a steady VR throughout the measurements. However, a steady decrease of tracer gas concentration was not always evident during the experiments due to the highly fluctuating airflow in the barn, which was driven by erratic outdoor wind velocity.

3.3   Air velocity through the inlet openings

The VR throughout the barn is the sum of airflow rates through all inlets.   The average air velocity V_{ave} (m/s) through any opening can be found by integrating the air velocity V (m/s) over the height H (m) of that opening from the bottom of the opening H_{bo} (m) to the top of the opening H_{top} (m) according to Equation (2) (Demmers et al., 2001).

$$V_{ave} = \frac{1}{H} \int_{H_{bo}}^{H_{top}} V(h)dh \qquad (2)$$

The measurements of air velocity were carried out using vane anemometers (Anemometerbau Dresden Nr.27, Germany), which were installed along the side wall of the dominant wind direction to measure the speed of entering air.   These vane anemometers were located at three different heights (high level = 0.3 m, middle level = 1.0 m and low level = 1.7 m under the eaves; Figure 2 and 4).   This arrangement of anemometers ensured a sufficient measuring accuracy at all openings in the side wall facing the prevailing wind direction (as described in chapter 3.1), considering also the various adjustments of side plastic curtains.   Each anemometer delivered values of air speed with a sampling rate of one record per minute (frequency = 0.017 Hz).   In practice, it is difficult to define the inlet or outlet areas due to varying meteorological conditions.   Because of changing wind directions an inlet can become an outlet and vice versa. Therefore, the estimation of the total *VR* through an outlet or an inlet is not reliable (Özcan, Vranken, and Berckmams, 2009).   Therefore, the airflow should be measured at all openings that are assumed to be inlets. In this study, an average air velocity was calculated for each window and then the *VRs* through the different windows were summed (Equation (3)).

$$VR = 3600 \times \sum_{i=1}^{i=n} (V_{ave,n.} \times S_n) \qquad (3)$$

where, *VR* is the total *VR* (m^3/h) through the whole barn; n is the number of windows; V_{ave} is the average air velocity through one window (m/s); and S is the opened vertical area of the single window (m^2).

3.4   Natural ventilation method

Natural ventilation is induced by wind pressure and thermal buoyancy forces.   The thermal buoyancy occurs in naturally ventilated animal barns independent of the outside wind conditions.   However, the actual VR from any opening is not equal to the sum of the two estimated quantities from wind effect and thermal buoyancy (Hellickson and Walker, 1983).   It is also not linearly proportional to pressure difference (Albright, 1990). Field experience and comparisons with relatively elaborate natural ventilation computer models have shown that the net rate of ventilation can be approximately estimated by the following Equation (4) (Albright, 1990; Hellickson and Walker, 1983; Kittas, Boulard, and Papadakis, 1997):

$$Q_{total} = \sqrt{(Q_{windforces})^2 + (Q_{thermalbuoyancy})^2} \qquad (4)$$

where, Q_{total} is the total VR (m^3/h); $Q_{windforces}$ is the *VR* due to wind forces (m^3/h); and $Q_{thermalbuoyancy}$ is the *VR* due to thermal buoyancy (m^3/h).

3.4.1   Ventilation rate due to the wind forces

The fluctuation of outside conditions limits the adaptability of a theoretical equation for determining the VR due to wind forces (Nääs et al., 1997).   In practice, the VR can be approximately estimated using empirical data in Equation (5) (Hellickson and Walker, 1983):

$$Q_{windforces} = 3600 \times EAV \qquad (5)$$

where, $Q_{windforces}$ is the *VR* due to wind forces (m^3/h); *E* is the effectiveness of the opening – a value of 0.35 is normally recommended for agricultural barns (Hellickson and Walker, 1983; Albright, 1990); *A* is the area of inlet opening (m^2); and *V* is the wind speed (m/s).

The determination of the effectiveness of the opening for typical naturally ventilated agricultural barns is very difficult (Bruce, 1986; Nääs et al., 1997).   In the literature, the effectiveness of the opening appeared uncertain.   Pearson and Owen (1994) presented discharge coefficients (C_d) between 0.45 and 0.98 for side openings.   Demmers (1997) estimated the C_d values for

space boarding between 0.43 and 0.46 for high and low wind cases, respectively.

3.4.2   Ventilation rate due to temperature difference forces

When the temperature inside a barn is different from that outside, pressure gradients are created because of a difference in air density.   When the inside temperature is warmer, the warm air will be displaced upwards by a buoyancy force. In the literature, this is also known as the chimney or stack effect.   The discharge velocity of air is directly proportional to the pressure difference and to the height between inlets and outlets.   The pressure difference can be converted to a temperature difference according to perfect gas laws.   Therefore, the discharge velocity resulting from thermal buoyancy can be calculated by Equation (6) (Hellickson and Walker, 1983):

$$V_{discharge} = \theta \sqrt{\frac{2gH(T_i - T_o)}{T_i}} \qquad (6)$$

where, $V_{discharge}$ is the discharge velocity (m/s); θ is a reduction factor for losses due to friction of the air against the inside surface of the duct; g is the acceleration of gravity (m/s^2); H is the height difference between inlet and outlet (m); T_i is the inside temperature (K); and T_o is the outside temperature (K).

Multiplying the velocity by the inlet area will produce the quantity VR due to thermal buoyancy (Equation (7)) (Hellickson and Walker, 1983):

$$Q_{thermalbuoyancy} = 3600 \times V_{discharge} \times A \qquad (7)$$

where, $Q_{thermalbuoyancy}$ is the VR due to thermal buoyancy (m^3/h); $V_{discharge}$ is the discharge velocity (m/s); and A is the area of the inlet opening (m^2).

3.5   Statistical analysis

The statistical analysis was carried out to evaluate the effect of the applied estimation methods, the outside wind velocity and the season on the VR throughout each barn. Twelve factor combinations were tested (three methods, two seasons - mild and cold, and two barrier options - barrier and free).   An ANCOVA model was fitted with the MIXED Procedure in SAS 9.2 (SAS Institute Inc. 2011, Cary, NC, USA) as follows:

$$VR_{fij} = \mu + S_f + M_i + (S \times M)_{fi} + B_j + X_1 \alpha + X_2 V + e_{fij}$$

$$(14)$$

where, VR_{fij} is the observed VR; μ is the general mean VR; S_f is the fixed effect of the fth season; M_i is the fixed effect of the ith applied method; $(S \times M)_{fi}$ is the fixed effect of the interaction between fth season and ith method; B_j is the fixed effect of the jth barrier option; X_1 is the regression coefficient of the covariable angle α between the wind direction and the side wall of the barn; X_2 is the regression coefficient of the covariable outside wind speed V; and e_{fij} is the normally distributed random residual.   The null hypotheses were that the fixed effects were equal to zero.   For testing of pairwise differences between effect levels, the SIMULATE adjustment for p-values was used to keep the global significance level of 0.05.

4   Results and discussion

The *r*adiation counters detected the impulses of radioactive isotope ^{85}Kr over the time.   Each counter could deliver a probable value for the air exchange rate at the counter position, if there was a clear regression in the obtained impulse curve for this point.   A clear regression could usually be found over a period between one and two minutes.   Even if this regression took place over a short time (e.g., 30 s), the estimated value was taken into account.   Analysis of the collected data showed strong variations of the decay functions between the different locations of the counters.   High air velocities caused a faster dilution of the tracer gas concentration within the barn than low air velocities, and therefore, higher air exchange rates occurred.   Additionally, the decay behavior in the open barns became highly variable at each measuring point due to the airflow pattern distribution. These phenomena agree with the study by Van Buggenhout et al. (2009).   They found large variations in the *VR* depended on the sampling positions because of non-perfect mixing of tracer gas and the air.   According to their study, measurement errors can rise to 86% of the actual *VR*, and the sampling positions near the air outlets showed the lowest errors.   Additionally, the dosing method has a significant influence on the decay behavior. Thus, the estimated value from each counter did not represent the overall air exchange rate in the whole barn and may in fact be far from its actual value.

According to Equation (1), $C(t_0)$ is considered the concentration of tracer gas at time t_0.   Time t_0 represents the start of the experiment, when the tracer gas was completely injected and mixed with the barn air.   In practice, $C(t_0)$ was taken as the beginning of the regression in the impulse curve.   Figure 5 shows an example of an impulse curve for one counter, where the gradient of the line represents the air exchange rate (which amounts to 0.0272 per second in this case).

A few counters showed clear decay of the obtained impulse curve (as in the example shown in Figure 5), and only those counters could deliver plausible air exchange rate values for the single location at different times during the experiments.   Otherwise, a single value from a single counter for the air exchange rate may represent a vortex at the counter location during the interval of the regression.   Therefore, the individually obtained values for the air exchange rate, according to individual evaluations of the counters, as well as the average of them, did not represent the actual air exchange rate throughout the whole barn.   In contrast, the rest of the data, which showed several fluctuations in the impulse curve, were excluded from the analysis.   Therefore, a new evaluation procedure was used for the [85]Kr data that were gathered, which takes the sum of impulses for all counters as a dependent variable on time (Figure 6).
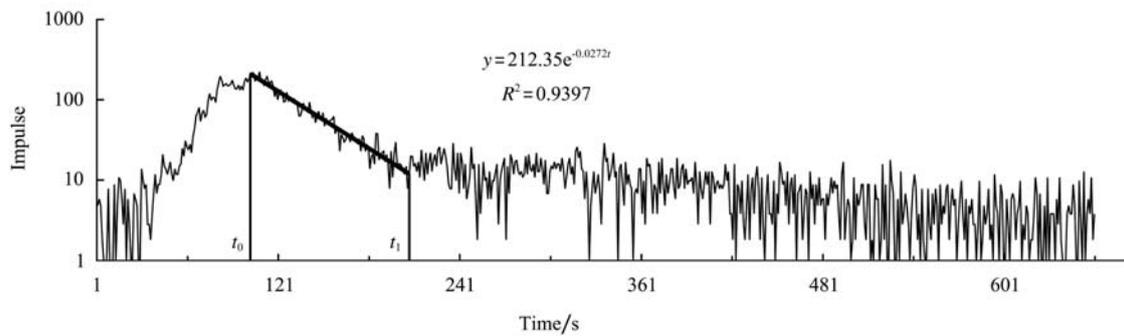

Figure 5   Impulse curve of one counter for radioactive gas [85]Kr (barn B, 19 Oct.), where the decay of the
red line represents the air exchange rate (which amounts to 0.0272 per second in this case)

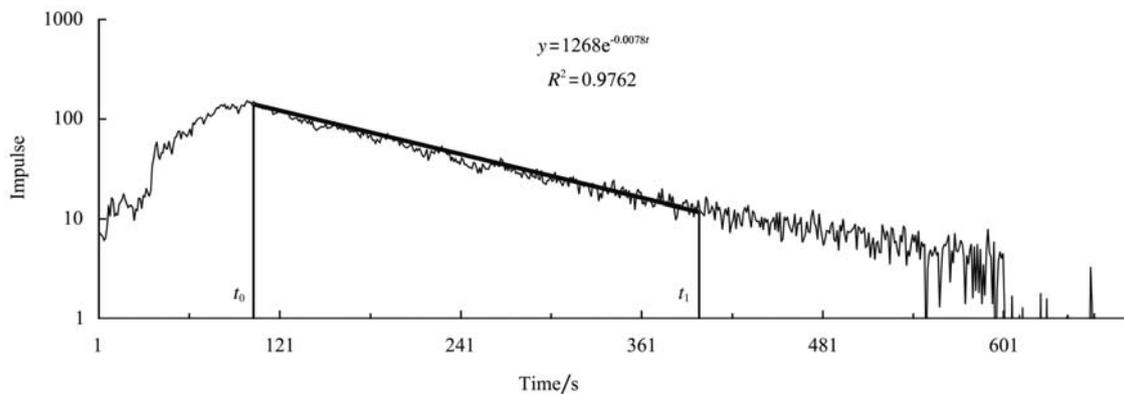Figure 6   Sum of impulses for all counters of [85]Kr (barn B, 19 Oct.)

During each experiment, the tracer gas was completely injected within the 1st min, but the counters took more time to record the maximum value of all impulses.   For the investigation performed, the data analyses showed that the tracer gas technique could deliver reasonable values for VRs only when the selected clear regression in the impulse curve lasted more than 2 min.   For impulse curves that lasted less than approximately 2 min, the regression curves for calculating the concentration decay had a weak coefficient of determination.   Therefore, only those values obtained from impulse curves that lasted more than 2 min and had a strong degree of determination were taken included in the statistical analysis.   The remaining values, which lasted less than 2 min, were excluded from the analysis.   It was found that the regression curve for

the sum of impulses for all counters showed more stability and fewer fluctuations than the individual regression curve for each counter; at least, then, the regression curve for the sum of impulses for all counters could deliver plausible values for the air exchange rates for all the experiments.   According to this evaluation procedure, the entire set of raw data was used, and better regressions in the impulse curves were found for all experiments.   Otherwise, the obtained curve of the sum of the impulses was not affected by the vortexes that occurred near some counters.   The new procedure only considers the amount of tracer gas that remains inside the barn over time (Kiwan et al., 2010).   For the abovementioned reasons, the sum of impulses for all counters can deliver representative results on the VR of the barn.

Air speeds through the openings varied over the whole area of the window.   Figure 7 shows the differences in air speeds at different locations in one window.   The high fluctuation in air speeds depended on the measurement location.   The air speeds in the middle measurement level (Figure 7, anemometers A12 and A14) were higher than in the upper and lower levels.   This finding is in agreement with theoretical calculations (Hellicksen and Walker, 1983) and with the study by Özcan, Vranken, and Berckmans (2009).   They investigated the velocity profile at a naturally ventilated opening and found the highest air velocities at the center of the opening.
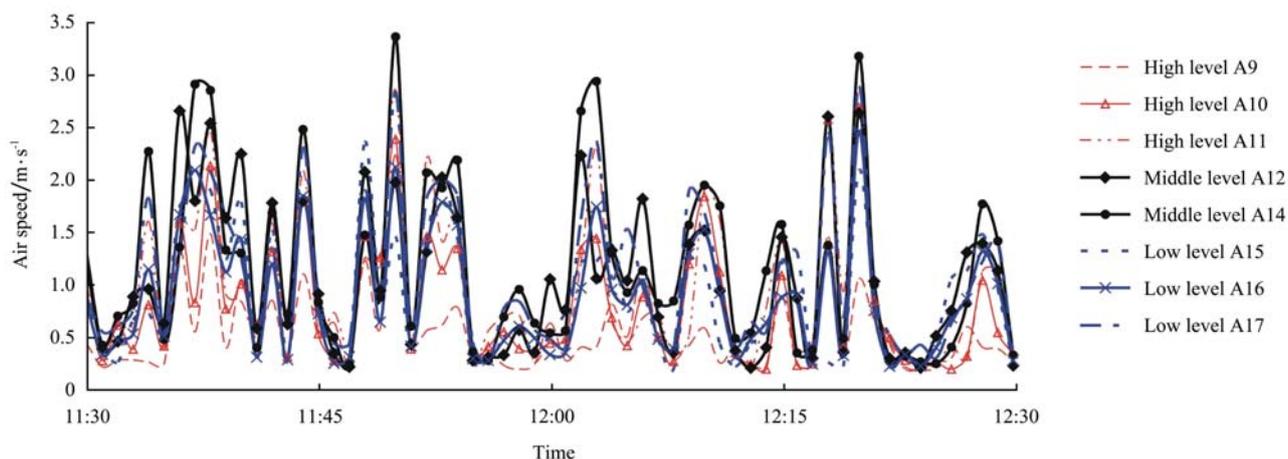

Figure 7   Air speeds at different points, in three horizontal levels (high level = 0.3 m, middle level = 1.0 m and low level = 1.7 m under the eaves; Figure 4), and in one window in barn B

Figure 8 shows the air velocities at different points in the same (middle) horizontal level in different windows along the side wall.   The air velocities at these various locations along the side wall and at the mid-horizontal level did not show any clear relationship among themselves.   Thus, for the calculations of VRs, the height (horizontal level) of the measuring point was considered more important than the location of the window along the side wall.   This finding indicates that it is more important to measure the air velocity at different points of an opening to obtain representative data for the entire opening (window) than to measure at a high number of openings that are located in very similar positions.

Figure 9 shows the calculated VR based on the tracer gas technique, air velocity measurements, and the natural ventilation method.   Most of the values ranged between 100,000 m^3/h   and   200,000 m^3/h.   Generally,   the estimated values of VRs, according to the three methods investigated, showed similar tendencies and were close together.   However, the VR values obtained from the air velocity through the inlet openings were mostly higher than the estimated values using the other techniques, whereas the tracer gas technique showed the tendency to estimate lower VR values than the air velocity method. An influence of the wind angle (0° means parallel to the side walls, and 90° means normal to the side wall) was not observed.
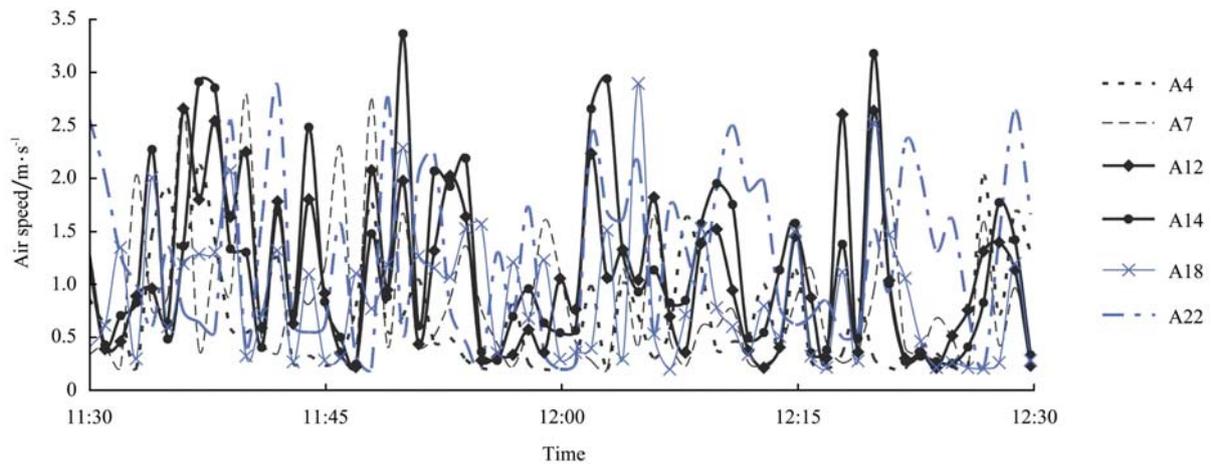
Figure 8   Air speeds at different points in the middle horizontal level in different windows along the side wall of barn B
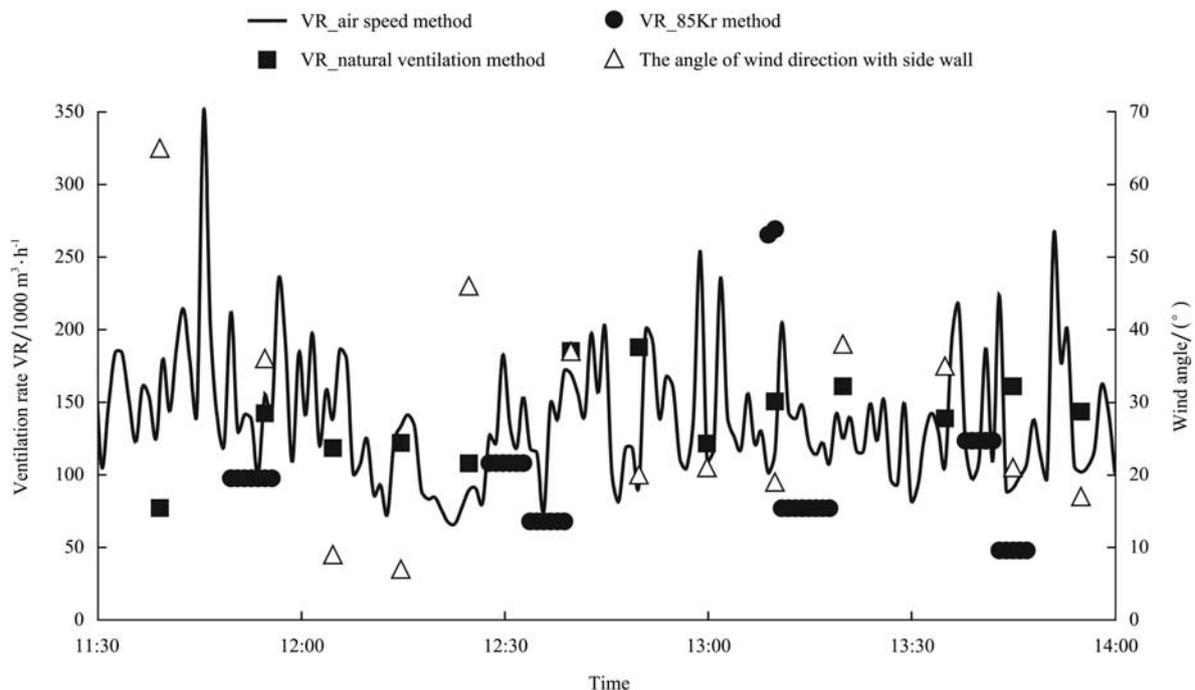

Figure 9   Ventilation rates (VR) in barn A based on the tracer gas technique, the natural ventilation method,
and on the air velocity measurements taken at the windows

Table 1 and Table 2 show the numeric values of VRs in barn A and B based on the three investigated methods. In addition, the angle α between the wind direction and side wall of the barn is given. When the wind direction is parallel to the barn side wall, $\alpha = 0°$, if the wind is approaching normal to the side wall, $\alpha = 90°$.   The VRs estimated based on the measurement of the air velocity through the openings showed the tendency to deliver higher values than the other two methods.   There were only slight differences between the results of the tracer gas technique and the natural ventilation method.   The

VRs of both barns, estimated using the three different methods, represented specific VRs between 250 m³/h and 1,200 m³/h per AU (AU = animal unit = 500 kg body mass).   As illustrated in Figure 9 and apparent in Table 1 and Table 2, VRs throughout the barns were fluctuating. However, the minimum estimated VR was at least several times higher than the minimum required value (100 m³/h per cow according to CIGR, 1984) needed to keep CO_2 concentrations below the recommended harmful limits. Fiedler and Müller (2011) measured VR in two dairy barns, also located in northeast Germany.   They used the

concentration decay of the tracer [85]Kr, as performed in this study. The estimated specific VRs ranged between 1,140 m³/h and 1,380 m³/h per AU. The barns in their study had larger openings than the barns in this investigation, which is consistent with the different specific VRs. Seedorf et al. (1998) reported specific VRs for dairy barns with cubicles from 176 m³/h to 647 m³/h per AU, which corresponds to the majority of our values. Snell, Seipelt, and van den Weghe (2003) measured VRs in four dairy barns, also by means of tracer concentration decay, but used SF_6 as the tracer gas. They found specific VRs between 260 m³/h and 930 m³/h per AU, which are very similar to our results. Ngwabie et al. (2009) reported specific VRs, calculated based on the CO_2 mass balance, of 401 m³/h per AU in the spring and between 250 m³/h and 265 m³/h per AU in the winter. The results of this study were difficult to compare with the results reported in other literature, partly because of incomplete information in the literature. Nevertheless, it can reasonably be concluded that the VRs estimated in this study were in good agreement with the other studies.

Table 1   Ventilation rates in barn A based on the three methods investigated and the angle α (°) between the wind direction and the side wall of the barn ($\alpha = 0°$ – wind is parallel to the side walls, $\alpha = 90°$ wind is normal to the side wall)

Experiment	Ventilation rate (1,000 m³/h) estimated by			$\alpha/(°)$
	Tracer gas technique	Air velocity through the openings	Natural ventilation method	
1	211.5	182.0	132.2	68
2	219.5	299.0	213.3	82
3	404.0	359.2	199.3	76
4	208.2	231.7	211.8	18
5	97.6	145.6	164.4	23
6	108.0	139.7	107.1	46
7	67.8	127.6	109.4	37
8	77.0	137.4	162.4	19
9	123.4	124.7	136.7	35
10	48.0	121.9	151.4	21

Table 2   Ventilation rates in barn B based on the three methods investigated and the angle α (°) between the wind direction and the side wall of the barn ($\alpha = 0°$ – wind is parallel to the side walls, $\alpha = 90°$ wind is normal to the side wall)

Experiment	Ventilation rate (1,000 m³ h⁻¹) estimated by			$\alpha/(°)$
	Tracer gas technique	Air velocity through the openings	Natural ventilation method	
1	168.2	200.5	272.9	76
2	124.9	157.8	225.9	71
3	311.3	361.4	334.5	63
4	265.4	474.7	334.5	63
5	159.2	254.8	190.2	23
6	171.5	256.2	210.1	62
7	89.8	127.1	148.0	31

The VRs, estimated with the three different methods, were compared with one another with Pearson's correlation coefficients for each barn (Table 3). The estimated VRs throughout barn A were correlated for each pair of comparisons with an associated p-value of less than 0.01. The highest Pearson's correlation coefficient (0.86) was found between the air velocity measurements through the inlet openings and the natural ventilation method, with an associated p-value of less than 0.0001. In barn B, a good correlation was found only between the tracer gas technique and the natural ventilation method, with an associated p-value of 0.03. Only a weak correlation was found between the tracer gas technique and the air velocity measurements through the inlet openings. The different surroundings, and therefore, the different approaching wind flows of both barns, could be considered as reason for these different correlations found for barn A and barn B. Wind could not approach the sidewalls of barn B without obstacles, except for at the small gable, whereas, at barn A, the wind could approach at least the southeast sidewall without obstacles.

Table 3   Correlations between the ventilation rates estimated by the three methods investigated, as tested by Pearson correlation analysis.

Method		Barn A		Barn B	
		Pearson's Correlation Coefficient	Associated p-Value	Pearson's Correlation Coefficient	Associated p-Value
Tracer gas technique	Air velocity measurements	0.6321	0.0049	0.5580	0.0594
Tracer gas technique	Natural ventilation method	0.5917	0.0097	0.6149	0.0334
Natural ventilation method	Air velocity measurements	0.8574	<0.0001	0.0618	0.8487

Zhang et al. (2005) investigated the air exchange rate throughout nine naturally ventilated dairy barns using SF_6 as a tracer gas and CO_2 mass balance. They released the tracer from a single point source and stated that the tracer gas technique has the disadvantage of achieving a perfect mixing between the SF_6 and the air inside the barn, especially in windy weather. Additionally, they mentioned that the CO_2 mass balance is based on steady-state data, which may increase the uncertainty in the air exchange rate estimations in a short period of time. Samer et al. (2011a) investigated an open, naturally ventilated dairy barn for 364 cows. They found no (linear) correlation between the VRs estimated based on the natural ventilation method and the VRs estimated based on the CO_2 mass balance, although there were no large differences between the mean values. However, the VRs based on the tracer gas technique and on the CO_2 mass balance showed a good linear correlation. The tracer gas technique overestimated VRs compared with the VRs estimated with the natural ventilation method.

The effect of the season, the applied estimation method, the barrier effect of surrounding buildings, the angle α between the wind direction and the side wall of the barn, and the outside wind speed on the VR were predicted using the described statistical model. The

measurement season and the applied method had a significant effect on the estimated VR for both barns (Table 4). For barn A also the barrier effect of the surrounding buildings and the wind speed had a significant influence on the estimated VR, which is due to local and wind conditions. Wind from the southern to the eastern directions approached the sidewall of barn A without obstacles, whereas wind from the northern to the southwestern directions had to pass several other buildings before approaching the barn. This situation was different for barn B, where only wind from the northwestern to the southwestern directions approached the building without obstacles; direct wind could only approach the gable wall, which was closed and much smaller than the sidewall. The approaching wind from all other directions had to pass obstacles around barn B, and no sidewall could be approached freely. This is assessed as the main reason for no significant barrier effect for barn B. The outside wind speed was also different for both barns. For barn A wind speed had a wider range (0.8-5.3 m/s), which was a prerequisite to prove a significant effect on the estimated VR. In contrast, at barn B, wind speed varied in a range between 1.1 m/s and 2.5 m/s during all measurements, and no effect on VR could be demonstrated.

Table 4   Test of fixed effects according to the ANCOVA model.

Effect	Barn A				Barn B			
	Num DF	Den DF	F Value	p-Value	Num DF	Den DF	F Value	p-Value
Season	1	45	20.87	<0.0001	1	27	16.84	0.0003
Method	2	45	10.84	0.0001	2	27	7.05	0.0034
Season*Method	2	45	2.11	0.1332	2	27	1.88	0.1713
Barrier	1	45	44.19	<0.0001	1	27	0.02	0.8924
$\alpha/(^{\circ})$	1	45	2.61	0.1135	1	27	0.03	0.8599
Wind speed/m · s^{-1}	1	45	8.95	0.0045	1	27	4.12	0.0524

Note: Num DF: numerator degrees of freedom; Den DF: denominator degrees of freedom; α: angle between the wind direction and the side wall of the barn.

The differences between VR estimated by the three investigated methods and for the mild and the cold season were estimated with the method of least squares. This method was also used by Okuyama et al. (2009) to improve the precision of estimation and to evaluate the reliability of multi-zonal airflow measurements. Table 5 contains the results for all comparisons where significant differences were found. In general, VR was higher in

the mild season, when the side curtains were opened, compared with the cold season, when the side curtains were partly closed. In barn A, VR was higher in the mild season by 84,546±37,141 m^3/h than in the cold season; in barn B this value was 187,093±57,819 m^3/h. The air velocity method resulted in a significantly higher VR in barn A (by 92,735±19,179 m^3/h) compared with the natural ventilation method. The differences between

the natural ventilation method and the tracer gas technique were significant in both barns.   However, the tracer gas technique produced a higher VR in barn A (by $61,059\pm19,179$ m^3/h), but a lower VR in barn B (by $81,646\pm27,521$ m^3/h) when compared with the natural ventilation method.   Additionally, in other investigations, both were found: underestimation of the tracer gas technique and overestimation in comparison to natural ventilation theory, CO_2 mass balance and heat balance (Samer et al., 2011b).   Two and three combinations of the factors method and season showed significant differences between barn A and barn B, respectively. For barn A, a significant interaction effect between the air velocity method and the natural ventilation method was observed for both seasons.   In barn B, a significant interaction effect between the air velocity method and the natural ventilation method, as well as between the tracer gas technique and the natural ventilation method, were observed for the mild season.   Finally, in barn B, the natural ventilation method resulted in a higher VR in the mild season (by $246,122\pm65,977$ m^3/h) compared with the cold season.

Table 5   Differences of least square means of ventilation rates (m^3/h)

Barn	Effect	Method / Season	Estimate	SE	Adj P
A	Method	AV-M & NV-M	92,735	19,179	<0.0001
A	Method	TG-M & NV-M	61,059	19,179	0.0078
A	Season	Mild & Cold	84,546	37,141	0.0289
A	Method * Season	AV-M$_{mild}$ & NV-M$_{mild}$	126,371	33,828	0.0055
A	Method * Season	AV-M$_{cold}$ & NV-M$_{cold}$	59,098	18,082	0.0202
B	Method	TG-M & NV-M	-81,646	27,521	0.0150
B	Season	Mild & Cold	187,093	57,819	0.0035
B	Method * Season	AV-M$_{mild}$ & NV-M$_{mild}$	-104,340	31,778	0.0249
B	Method * Season	TG-M$_{mild}$ & NV-M$_{mild}$	-118,143	311,778	0.0090
B	Method * Season	NV-M$_{mild}$ & NV-M$_{cold}$	246,122	65,977	0.0086

Note: TG-M: tracer gas method; AV-M: air velocity method; NV-M: natural ventilation method.

5   Conclusions

The concurrent investigation of three methods to estimate VR throughout naturally ventilated dairy barns provided new knowledge on these methods as well as further development of the tracer gas technique and the air velocity measurement through inlet openings.   The analysis of the tracer gas technique led to the conclusion that it is appropriate to summarize the data of all single measuring points to one decay curve and calculate one regression curve (from this decay curve) that represents the VR of the whole barn, instead of calculating single regression curves for each measuring point and then averaging the single VRs (to one value).   The measurements of the wind fields within the inlet openings of the barns confirmed theoretical calculations and delivered more specific information on dairy barns.   For VR estimation based on air velocity measurements, it was concluded that it is more important to measure the air velocity at different points within an opening to obtain representative data for the whole opening than to measure at a high number of openings which are located in very similar positions.   The three methods investigated showed a generally good correlation with each other (0.59–0.86; $p \leq 0.03$).   Only when the wind approaching the barn had to pass surrounding obstacles, there was no linear correlation between the air velocity measurements through the inlet openings and the tracer gas technique, (0.56; $p = 0.06$; 0.06; $p = 0.85$, respectively).   Air velocity measurements through the inlet openings of a naturally ventilated dairy barn are an option to estimate VR, but outside wind conditions (including surrounding obstacles) have to be considered as well.   The tracer gas technique is promising for the estimation of VR through naturally ventilated dairy barns and merits further development.

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