A COMPREHENSIVE STUDY ON DIFFERENT ETHODS FOR AIR EXCHANGE RATES EASUREMENT IN A NATURALLY VENTILATED DAIRY HOUSE

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ABSTRACT

The major problem of natural ventilation is the lack of accurate, continuous and online measuring and controlling techniques for air exchange rates (AER) which is crucial for the quantification of gaseous emissions. Therefore, this papers aims at comparing four measurement methods and to recommend thereof one method for further developments. Thirty six experiments were performed to study the AERs in a naturally ventilated dairy barn through four summer seasons and three winter seasons. The AERs were determined using moisture (H_2O) balance, heat balance (HB), CO_2-balance and tracer gas technique (TGT). The statistical analyses were correlation analysis, regression model, ANOVA model and t-test. Continuous measurements of CO_2 concentrations, temperature and relative humidity inside and outside the building were performed. The H_2O-balance showed reliable results through winter seasons and slightly acceptable results through summer seasons. The error sources of H_2O-balance are: the difference between the internal and external humidity levels which depend in turn on the accuracy of the used temperature-humidity sensors and their locations, the correctness of the used factors (e.g. the moisture produced by one cow and per mass unit), and the accuracy of the calculations of the humidity ratios. The HB showed acceptable results to some extent through summer seasons and unsatisfactory results through winter seasons. The error sources of HB are: the calculations accuracy of the net area of the different building components and the determination of the relevant overall heat transfer coefficients, the temperature difference which depends in turn on the accuracy of the used temperature-humidity sensors and their locations,

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and the sensible heat produced by the animals which depends on the physiological changes of the animals. The CO_2-balance showed unexpected high differences to the other methods in some cases. The error sources of CO_2-balance are: the use of calculation models for metabolic energy, the amount of CO_2 produced per energy unit, the quantity of CO_2 produced emitted from manure, variations of ambient temperatures and the location of CO_2 measuring points. The TGT showed reliable results compared to HB, H_2O-balance and CO_2-balance. Therefore, the TGT should be further developed, where it delivers comparable results and is independent on the physiological parameters. The airflow rates (AFRs), subject to TGT, were 0.12 m^3 s^{-1} m^{-2}, 1.15 m^3 s^{-1} cow^{-1}, 0.88 m^3 s^{-1} LU^{-1} (LU is livestock unit of 500 kg), 395 m^3 s^{-1} and 470 kg air s^{-1} through summer seasons, and 0.08 m^3 s^{-1} m^{-2}, 0.83 m^3 s^{-1} cow^{-1}, 0.64 m^3 s^{-1} LU^{-1}, 275 m^3 s^{-1} and 328 kg air s^{-1} through winter seasons. The AERs were 37, 81, 63 and 62 h^{-1} through summer seasons, and 40, 143, 61 and 39 h^{-1} through winter seasons subject to H_2O-balance, HB, CO_2-balance and TGT, respectively.

Keywords. Livestock buildings, Heat balance, Moisture (H_2O) balance, Tracer gas technique, CO_2-balance, Natural ventilation, Airflow rates, Air exchange rates, Gaseous emissions.

INTRODUCTION

Natural ventilation is the movement of air through openings of a building by the use of the natural forces produced by wind and temperature difference. Simplicity, low initial costs and low energy costs are primary factors that make the natural ventilation most common type of ventilation. However, natural ventilation that is dependent on natural forces is inherently variable and consequently has numerous limitations (Hellickson and Walker, 1983). Ventilation measurements provide the means for understanding the mechanics of ventilation and air flow in the buildings (Liddament, 1996). According to Albright (1990), three important concepts underlie environmental analysis of buildings: (a) control volumes, (b) conservation of energy and (c) conservation of mass. The concept of energy conservation is applied to sensible heat, and mass conservation is applied to latent heat (humidity) and gaseous contaminants. In other words, the conservation of

energy is applied to heat balance, and the mass conservation is applied to H_2O-balance and CO_2-balance and the other gaseous contaminants. Hatem (1993) described some methods for ventilation rate measurements, thereof: heat balance, and CO_2 and H_2O mass balances. These methods largely depend on the animal production of heat, CO_2 and H_2O. Sallvik (1999) elucidated the heat balance at animal level and the animal heat production. Teye and Hautala (2007) investigated the heat balance, CO_2-balance and H_2O-balance. They concluded that the aforementioned methods are adequate for estimating the ventilation rates in naturally ventilated buildings.

Samer et al. (2011a) compared the radioactive tracer gas technique to two other methods for ventilation rate measurements, which are: CO_2-balance, and the combined effects of wind pressure and temperature difference forces (WT-method). They found a good linear correlation between tracer gas technique and the CO_2-balance, but they found no linear correlation between tracer gas technique and the WT-method which depends on wind velocity (speed and direction) that varies from moment to moment. On the other hand, the CO_2-balance depends on animal production of CO_2 which in turn depends on the metabolic energy. Therefore, they recommended further developing the radioactive tracer gas technique which delivers comparable results and is independent on physiological changes. Samer et al. (2011b,c) developed further the radioactive tracer gas technique and they concluded that the sum of radioactive impulses calculation method lead to better results. They added that considering all readings of the radiation counters is more representative for air movement. Samer et al. (2011b) stated that the release of radioactive tracer gas orthogonal to the prevailing wind at the windward side (over the manure alley) produced better detection by all radiation counters through summer seasons emphasizing better mixing of tracer gas with air and the better distribution of tracer inside the livestock building. Samer et al. (2011c) stated that the release of radioactive tracer gas from a fixed source point determined with smoke experiments is the best suited release method through winter seasons where the barn is totally closed.

The determination of ventilation rates through naturally ventilated buildings is a key factor in quantifying emission flow rates from livestock buildings. There is a need to improve the accuracy of ventilation rate measurements because no accurate, reliable, and online method is available for ventilation rate measurement in naturally ventilated barns. Therefore, the objective of this study was to evaluate and compare the ventilation rates estimated using the following measurement methods: radioactive tracer gas technique, heat balance, H_2O-balance and CO_2-balance. This paper summarizes the investigations carried out by Samer et al. (2011d, 2012).

MATERIALS AND METHODS

Specifications of the Barn

The measurements were carried out during 4 summer seasons and 3 winter seasons, in a naturally ventilated dairy barn located in north-east Germany (at latitude of 54° 1' 0" N, longitude of 12° 13' 60" E, and altitude of 43 m). The investigated dairy barn is surrounded by several agricultural buildings, except the southern and western sides. Fortunately, the prevailing summer winds are south to south-west winds. The dairy barn was 96.15 m long and 34.2 m wide. The roof top varied from 4.2 m at the side to 10.73 m at the gable top. The internal room volume of the barn amounted to 25,499 m³ (70 m³ cow⁻¹), where the barn is designed to accommodate 364 dairy cows in loose housing system with freestalls. The manure handling system was equipped with winch-drawn dung channel scrapper. The dairy barn was naturally ventilated by air draft introduced into the building through adjustable curtains in the sidewalls (which were protected by nets and open in summer but closed in winter), open ridge slot, space boards of the gable walls, and open doors in the gable walls. During the summer seasons, three additional ceiling fans were used to enhance the uniformity of air distribution inside the barn. The fans were mounted to the ceiling along the building centerline and had a diameter of 7.2 m with a maximum discharge of 546,000 m³ h⁻¹ .

Experimental Procedures

The measurements were conducted over 2-week period per season, where the air temperature and relative humidity were measured inside and outside the building using 6 temperature-humidity sensors/loggers

(THS). Furthermore, the concentration of CO_2 was continuously measured, using a multi-gas monitor (INNOVA 1312, Innova AirTech Instruments, Ballerup, Denmark), inside the barn at 8 uniformly distributed sampling points (SP) and outside the barn at 4 points (Fig 1). A radioactive tracer gas was used for ventilation rate measurements, where the radioactive impulses were measured using 20 radiation counters (RC). The results were compared by performing Pearson correlation analyses and developing linear regression models as well as t-test. The differences to the reference method were tested using ANOVA model. The statistical analyses were conducted with SAS v.9.2 (SAS Institute, Cary, USA).
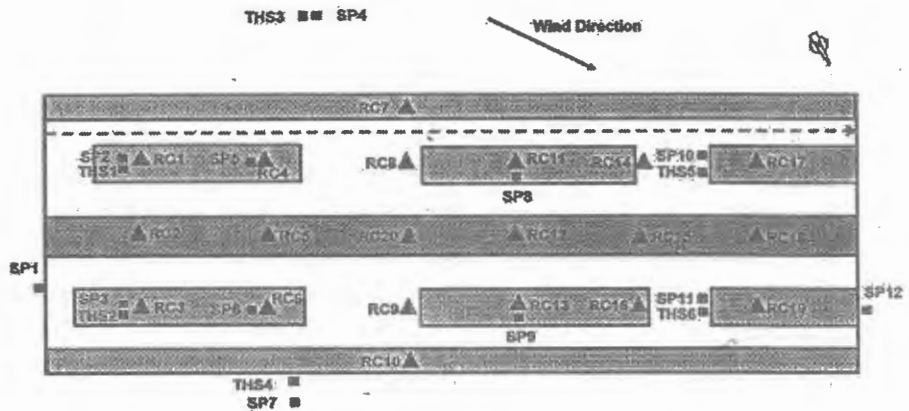

Figure 1. Plan view of the investigated barn, where RC is radiation counter, SP is gas sampling point, and THS is temperature-humidity sensor (Samer et al. 2012).

Tracer Gas Technique

The trace gas under consideration was Krypton-85, where the decay method of radioactive isotope [85]Kr was implemented. The tracer experiments were conducted between 4 and 6 times per campaign, i.e. investigation period. The tracer gas was released inside the building to determine the air exchange rate using the decay method, where ideal mixing of both air and tracer gas inside the building was assumed. The

air exchange rate is then the result of an exponential relation between the impulses and the time. The tracer gas was released from a line source on the windward side of the building, orthogonal to the prevailing wind, over the manure alley (orange dash line, see Figure 1). Thirty six tracer gas experiments were conducted from 2006 to 2011, where 16 were in summer and 20 in winter. The duration of each tracer gas measurement was approx. 10 min including the release, decay, and idle time. The radioactive tracer gas was constantly released during each investigation and the decrease of impulses was measured for each release. Uncertainties with this method can be caused by inadequate mixing of the tracer gas in the air plenum of the building. The ventilation rate was calculated using the decay method of radioactive [85]Kr as follows:

$$I = I_0 \cdot e^{-\alpha \cdot t} \tag{1}$$

$$\dot{V}_{TGT} = \alpha \cdot v \tag{2}$$

Equation (2) is an exponential function, where I represents the impulses recorded by the radiation counters per second, t is the time in seconds, α (s-1) represents the air exchange rate per second, and I0 is the impulses at t=0 (Gläser et al., 1986). The term α (s-1) should be converted to air exchange rate per hour in order to be used in Eq. (7) where, v (m3) is the volume of the building, and $\dot{V}_{TGT}$ (m3 h-1) represents the ventilation rate estimated using the tracer gas technique.

H2O-Balance

Moisture, formed by animal respiration and by evaporation from manure and forages, can be used as a natural tracer gas. The ventilation rate throughout the building can be determined by calculating the mass balance of H2O flow. The calculations of moisture balance were based on several studies (Albright, 1990; Hellickson and Walker, 1983; Teye and Hautala, 2007). The following mathematical model describes the moisture balance:

$$Q_{H_2O} = \frac{v \cdot M_W}{W_i - W_o} \tag{3}$$

Where, Q_{H_2O} (m^3 s^{-1}) represents the ventilation rate subject to the H$_2$O-balance, v (m^3 kg^{-1} dry air) is the air specific volume, W_i (g H$_2$O Kg^{-1} dry air) is the humidity ratio inside the building and W_o (g H$_2$O Kg^{-1} dry air) is the humidity ratio outside the building. The humidity ratios were determined by the psychometrics software EZAir Properties v.1.3.5 (R. M. Parks, Gradyville, PA, USA) using the relative humidity and temperature measured by the temperature-humidity sensors. M_W (g H$_2$O s^{-1}) represents the moisture produced by the cows housed in the building, and was calculated as follows:

$$M_W = n \cdot m_W \tag{4}$$

$$m_W = P_{H_2O} \cdot M_{avg}. \tag{5}$$

Where, n represents the number of cows housed in the building, mW (g H2O s-1) is the moisture produced by one dairy cow, Mavg. (kg) is the average mass of the cows, and P_{H_2O} (g H2O h-1 kg-1) is the moisture produced by a dairy cow per mass unit which is 1.8 (Lindley and Whitaker, 1996).

Heat Balance

The heat balance was calculated as follows (Hellickson and Walker, 1983; Albright, 1990; Lindley and Whitaker, 1996):

$$\dot{V}_{HB} = \frac{q_s - (\Sigma UA + FP) \cdot (t_i - t_o)}{C_p \cdot \rho \cdot (t_i - t_o)} \tag{6}$$

Where, $\dot{V}_{HB}$ (m3 s-1) represents the ventilation rate, subject to the heat balance, and is later converted from m3 s-1 to m3 h-1 to be comparable with the other methods; q_s (W) is the sensible heat produced by the animals and is estimated using the energy calculation model (Samer et al., 2011b); U (W m-2 oC-1) represents the overall heat transfer coefficient of the building component under consideration and A (m2) is its area; the factor ΣUA characterizes the overall conductance of the building shell and includes the effects of ceiling, walls, windows, and doors; F (W m-1 oC-1) represents the perimeter heat loss factor and was considered as 1.5 W m-1 oC-1 (Albright, 1990); P (m) is the perimeter

length of the building under consideration; C_p (J kg-1 oC-1) represents the specific heat of the air which was considered as 1006 J kg-1 oC-1 according to Albright (1990), ρ (kg m-3) is the air density and is the inverse of the specific volume which was derived from the psychrometric charts using the dray-bulb temperature and the relative humidity; t_i (oC) is the air temperature inside the barn, and t_o (oC) is the air temperature outside the barn.

CO_2-Balance

The carbon dioxide balance was calculated as follows (Hellickson and Walker, 1983; CIGR, 1984; Albright, 1990; CIGR, 2002):

$$\dot{V}_{CO_2} = \frac{n \cdot P_{CO_2}}{C_i - C_o} \tag{7}$$

Where, P_{CO_2} (mg h^{-1} cow^{-1}) represents the excretion rate of CO_2 from one cow, n is the number of cows housed inside the building, $\dot{V}_{CO_2}$ (m³ h^{-1}) is the ventilation rate calculated subject to CO_2-balance which was set as reference method, and C_i (mg m³) and C_o (mg m³) are the concentrations of the gas inside and outside the building, respectively. The air exchange rate can be then calculated by dividing the ventilation rate by the volume of the building.

RESULTS AND DISCUSSION

Generally, the H_2O-balance showed slightly acceptable results through summer seasons (Figs. 2a and 3a) on the one hand and reliable results through winter seasons (Figs. 2b and 3b) on the other hand. In summer, the H_2O-balance delivers comparable results to TGT and CO_2-balance. However, the overall deviations between the methods are too high, which does not allow specifying the most suitable method for summer. In winter, the H_2O-balance shows better results. Overall, all three methods showed good agreements in winter except for some inaccuracies in CO_2-balance. Provided some improvements to the CO_2-balance the three methods deliver similar and satisfactory results through winter seasons. The H_2O-balance has some error sources, which are: the difference between the internal and external humidity levels which depend in turn

on the accuracy of the used temperature-humidity sensors and the suitability of their locations, the correctness of the used factors (e.g. the moisture produced by one cow and per mass unit), and the accuracy of the calculations related to the humidity ratios.

The HB delivers comparable results to the TGT and CO_2-balance (Figs. 4a and 5a) through summer seasons and inaccurate results through winter seasons (Figs. 4b and 5b). However, the overall deviations between the methods are too high, which does not allow specifying the most suitable method due to the variable climatic conditions that affect all methods. Hence, all methods should be enhanced. Concerning the HB, the error sources are: the accuracy of the calculations related to the net area of the different building components and the determination of the relevant overall heat transfer coefficients, the temperature difference which depends in turn on the accuracy of the used temperature-humidity sensors and the suitability of their locations, and the sensible heat produced by the animals which depends on the physiological changes.
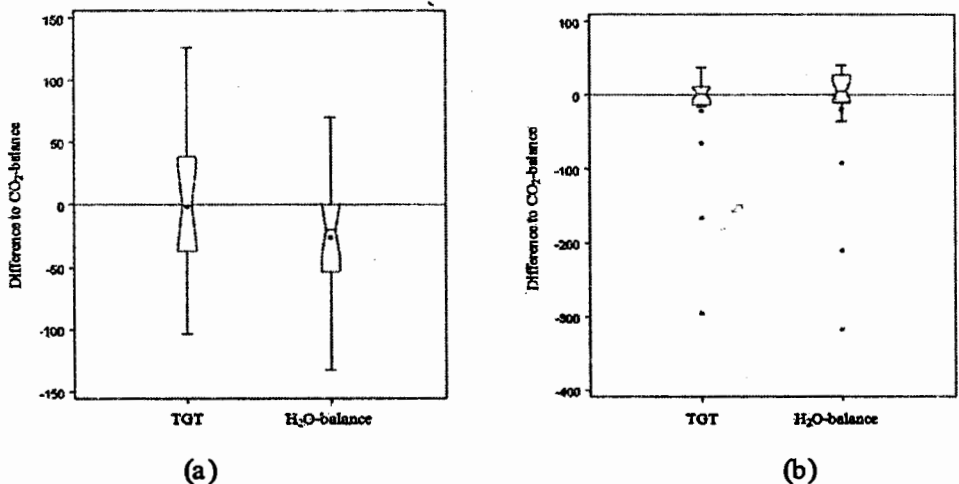

(a)   (b)

Figure 2. Distributions of the differences in h^{-1} between TGT and CO_2-balance on the one hand and H_2O-balance and CO_2-balance on the other hand, where (a) is for summer and (b) for winter. The solid dots represent the averages, the internal dashes designate the medians, and the upper and lower external dashes are the maximal and minimal values within 1.5 times the interquartile range (Samer et al. 2012).
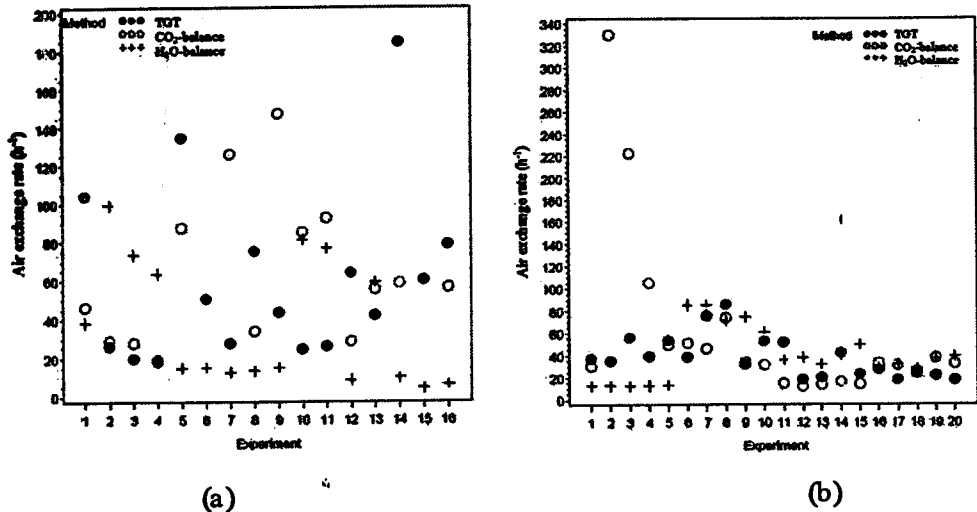
(a)   (b)

Figure 3. AERs subject to TGT, H_2O-balance and CO_2-balance during the different experiments, where (a) is for summer and (b) for winter (Samer et al. 2012).
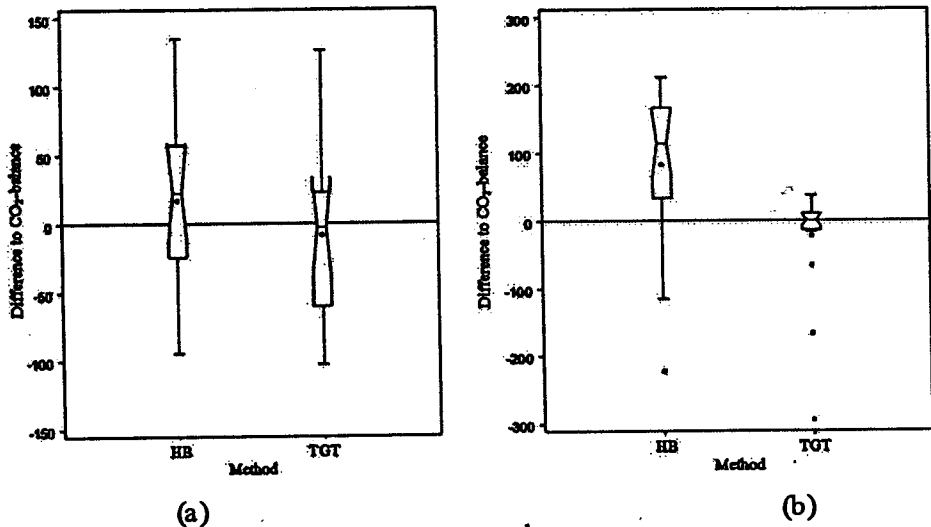

(a)   (b)

Figure 4. Distributions of the differences in h^{-1} between TGT and CO_2-balance on the one hand and HB and CO_2-balance on the other hand, where (a) is for summer and (b) for winter. The solid dots represent the averages, the internal dashes designate the medians, and the upper and lower external dashes are the maximal and minimal values within 1.5 times the interquartile range (Samer et al. 2011d).
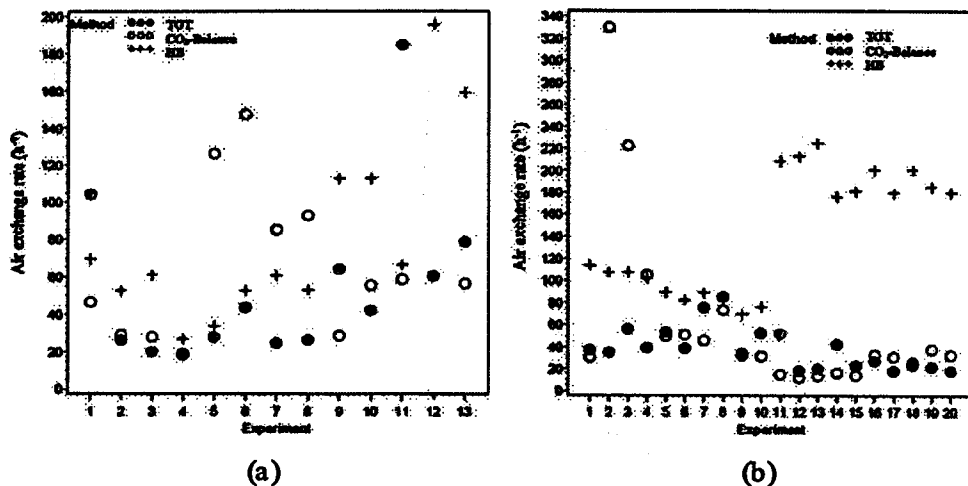
(a)   (b)

Figure 5. AERs subject to TGT, HB and CO_2-balance during the different experiments, where (a) is for summer and (b) for winter (Samer et al. 2011d).

The CO_2-balance is not in general use a reference to measure air exchange rates owing to several error sources that can have negative impacts, such as the calculation of metabolic energy, the CO_2 produced per energy unit, the amount of CO_2 produced by manure, and the location of the CO_2 sampling points. However, in this study, the CO_2-balance was set as a reference because comparison with other accurate methods is not possible. Hence, the CO_2-balance should be enhanced using the lowest CO_2 concentrations among the external measuring points to avoid overestimation through very low differences between internal and external CO_2 concentrations.

The TGT showed reliable results in comparison to H_2O-balance through winter seasons, and more accurate results through summer seasons. On the other hand, the TGT showed reliable results in comparison to the HB which showed slightly acceptable results through summer seasons on the one hand and unsatisfactory results through winter seasons on the other hand. Additionally, the TGT is more reliable than CO_2-balance that showed unexpected high differences to the other methods in some cases (Figs. 3b and 5b). Therefore, the TGT should be further developed,

where it delivers comparable results and is independent on the physiological parameters. Although the TGT was previously improved (Samer et al., 2011b, 2011c); further improvements are required and should focus on developing and enhancing the calculation method. The airflow rates subject to the different methods are summarized in Table1.

Based on the above, a perspective has been formulated which is implementing at least three measurement methods, to simultaneously measure the ventilation rate in a naturally ventilated building as follows: (1) TGT, CO_2-balance and HB in summer, and (2) TGT, CO_2-balance and H_2O-balance in winter. Besides, a fifth method can be implemented, which is the combined effect of wind pressure and thermal buoyancy, i.e. the WT-method, which was implemented by Samer et al. (2011a). When two of three measurement methods or three of four methods agree, the agreed value is then considered and the irregular value is ruled out.

Table 1. Airflow rates subject to the different methods (Samer et al., 2011d, 2012).

Season	Method	AER	$\overset{\bullet}{V}$	Airflow rate per unit area	Airflow rate per cow	Airflow rate per LU	$\overset{\bullet}{M}$
		h^{-1}	m^3 s^{-1}	m^3 s^{-1} m^{-2}	m^3 s^{-1} cow^{-1}	m^3 s^{-1} LU^{-1}	kg s^{-1}
Summer	HB	81.40	577	0.18	1.68	1.29	686
	H_2O-balance	37.21	264	0.08	0.75	0.58	314
	TGT	55.76	395	0.12	1.15	0.88	470
	CO_2-balance	64.34	456	0.14	1.32	1.02	542
Winter	HB	143	1014	0.31	3	2.31	1207
	H_2O-balance	40.26	285	0.09	0.86	0.66	339
	TGT	38.88	275	0.08	0.83	0.64	328
	CO_2-balance	60.46	428	0.13	1.29	0.99	510

The results differ from summer to winter; this can be attributed to the seasonal variations of temperature and humidity which affect the heat balance and the moisture balance, respectively. Additionally, the barn is totally closed in winter where the ventilation rate through a naturally ventilated barn is dependent on wind velocity (Samer et al., 2011e). Several studies were carried out to investigate the ventilation rate with radioactive tracer gas technique and recommended to developing further

this technique which is independent on physiological changes and variations of temperature and humidity (Samer et al., 2011f,g,h). A key issue is to monitor the climatic variations (wind velocity, temperature and humidity) outside the naturally ventilated building throughout the experiments using a weather station, and the indoor air temperature and humidity using temperature-humidity sensors as well as the indoor air velocity using anemometers where a computer program was developed for monitoring and controlling ultrasonic anemometers for aerodynamic measurements in animal housing (Samer et al., 2011e,i).

Safety Emphasis

Regarding the cows, the natural radioactivity of meat is 100 Bq kg^{-1} (LLBB, 2005). Through the TGT experiments, one cow receives 0.688 Bq kg^{-1}. Regarding the workers, adults have natural "internal" radioactivity of 9000-10000 Bq (BfS, 1993) owing to the fact that the body contains radioactive isotopes ^{40}K and ^{14}C. Through the TGT experiments, one worker receives 470.6 Bq. For more information regarding the safety of implementing radioactive tracer refer to Samer et al. (2011a,b).

CONCLUSIONS

Both H_2O-balance and CO_2-balance, which are mass balances, are able to continuously determine the ventilation rates through naturally ventilated buildings. However, they are dependent on physiological changes in animals and they have several error sources: locations of the different measuring points, calculation models, accuracy of H_2O and CO_2 production rates per animal unit or cow, and the amount of H_2O and CO_2 released from manure. The heat balance, which is a continuous ventilation rate measurement method, showed inaccuracies especially through winter seasons. The error sources of heat balance are: the accuracy of the calculations related to the net area of the different building components and the determination of the relevant overall heat transfer coefficients, the temperature difference which depends in turn on the accuracy of the used temperature-humidity sensors and the suitability of their locations, and the sensible heat produced by the animals which depends on the physiological changes in animals as bio-response to

changes in ambient micro-environmental conditions. The radioactive tracer gas technique showed reliable results in comparison to H_2O-blance, CO_2-balance and heat balance. Additionally, this technique is independent on physiological parameters and variations of temperature and humidity, and is safe. However, it is a discontinuous ventilation rate measurement method and is dependent on wind velocity (direction and speed). The overall deviations between the methods are high, which does not allow specifying the most suitable method due to the variable climatic conditions that affect all methods. Hence, all methods should be enhanced. A perspective is to implement at least three measurement methods, to simultaneously measure the ventilation rate in a naturally ventilated building as follows: (1) TGT, CO_2-balance and HB in summer, and (2) TGT, CO_2-balance and H_2O-balance in winter. Besides, a fifth method can be implemented, which is the combined effect of wind pressure and thermal buoyancy (WT-method). When two of three measurement methods or three of four methods agree, the agreed value is then considered and the irregular value is ruled out.

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الملخص العربى

دراسة شاملة لطرق مختلفة لقياس معدلات التهوية الطبيعية بمساكن الابقار الحلابة

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المشكلة الكبرى في التهوية الطبيعية هي عدم وجود طرق قياس دقيقه لمعدل تبادل الهواء (AER)وهو أمر حاسم لتقدير الانبعاثات الغازيه. يهدف هذا البحث إلى المقارنة بين أربعة أساليب، والتوصية بتستخدام أسلوب واحد مع تطويره. تم تنفيذ ستة وثلاثين التجارب لدراسة AERsفي حظيرة الألبان ذات تهوية طبيعية في أربعة فصول صيف، ثلاثة مواسم الشتاء. وتم تحديد AERs باستخدام ميزان الرطوبة (H_2O) ، ميزان الطاقة (HB) ، ميزان الكتلة لغاز CO_2, وتقنية التتبع الغازي بالمواد المشعة (TGT). كانت التحليلات الإحصائية تحليل الارتباط نموذج الانحدار، ANOVA واختبار t. وأجريت القياسات المستمرة للتركيزات CO_2ودرجة الحرارة والرطوبة النسبية داخل وخارج الحظيرة. وأظهرت نتائج ميزان H_2O انه يمكن الاعتماد عليها خلال فصل الشتاء ونتائج مقبولة قليلا خلال الصيف. وأظهر ميزان HB نتائج مقبولة قليلا خلال فصل الصيف ونتائج غير مرضية خلال فصل الشتاء. وأظهر ميزان CO_2اختلافات غير متوقعه مقارنة بالأساليب الأخرى في بعض الحالات. وأظهرت النتائج ان TGT هي الأفضل مقارنة بجميع الطرق ومستقلة على النواحي الفسيولوجية. ولذلك، ينبغي تطوير TGT .

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