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UNCERTAINTY ANALYSIS OF USING CO₂ PRODUCTION MODELS BY COWS TO DETERMINE VENTILATION RATE IN NATURALLY VENTILATED BUILDINGS

GUOQIANG ZHANG¹, SØREN PEDERSEN, PETER KAI

¹ G. ZHANG, Department of Biosystems Engineering, Faculty of Agricultural Sciences, Aarhus University, Denmark, Blichers Allé 20, Postboks 50, DK-8830 Tjele, guoqiang.zhang@agrsci.dk.

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ABSTRACT To provide accurate estimation of gas emission from livestock production facilities relies on the precision of the measurement of the ventilation flow and gas the concentration. However, it is difficult to make reliable direct measurements of the airflow exchange in naturally ventilated open type livestock buildings. Using tracer is one of the approaches to determine the ventilation flow rates. Application of an artificial tracer gas is complex, expensive, and may involve technical difficulties to make its distribution uniformly in the buildings. A feasible approach that has been applied by several published researches is using the CO₂ produced by livestock as tracer gas to estimate the ventilation airflow in open buildings. This paper reviewed the CO₂ production model and the field measurements of five dairy cattle buildings to estimate the feasibility of applying CO₂ production model to determine the ventilation airflow rates in naturally ventilated livestock buildings. The method of using CO₂ production model was compared with that of using an artificial tracer gas. The feasibility of estimating the ventilation rates based on the differences of the carbon dioxide concentration in and out of the building, and carbon dioxide production of the animals were addressed. Uncertainty of determination of ventilation rates based on CO₂ production model was analyzed. The most important questions on measurement positions and animal carbon dioxide production models were raised and discussed. The conclusion is that for open buildings, the methods based on animal CO₂ production as tracer gas achieve the similar accuracy as other methods using tracer gas.

Keywords: Carbon dioxide, Ventilation rate, Natural ventilation, Animal heat production, Cattle buildings.

1. INTRODUCTION

Ventilation airflow rate and concentration of the exhaust air from the ventilated enclosure are two major factors for estimation of the gas emission from a livestock building. Measurements of the ventilation rates can be performed by using some available techniques, e.g., nozzles, orifices, ultra-sonic sensors or free-propeller fans installed in the outlet ducts in a mechanically ventilated building. However, these methods are not directly applicable for naturally ventilated open buildings. A challenge is remained to

find alternative methods for estimating the ventilation airflow in open full scale livestock buildings. One possibility is to use tracer gases. However, application artificial tracer and make correct distribution in the building enclosure are often complicated, time consuming and expensive. As an alternative, the carbon dioxide produced by the animals in the building can be used as tracer gas. Based on the difference between the carbon dioxide concentration in the ingoing and the outgoing air, the ventilation flow can be determined. The total CO₂ production includes CO₂ produced by the animals and CO₂ emitted from the manure, which gives some limitations in the applicability.

The CO₂ production from the animal can be derived from its energy metabolism rate, which is related to feeding level and nutrient composition of the diet (Brouwer, 1965). In animal houses where the manure is not stored in the barn for a long period (e.g. the buildings with slatted floor and under-floor manure pits which are regular emptied), the CO₂ production from the manure handling system is small compared to the CO₂ production from animals. However, in animal houses with deep litter (i.e. animal houses where the depth of the litter is > 0.5m), the CO₂ production from the deep litter can be considerable why it is difficult to estimate the ventilation flow.

2. ESTIMATION OF AIR EXCHANGE RATE BASED MASS BALANCE OF CO₂

A general description of using mass balance method for estimation of the ventilation air exchange rates of a naturally ventilated open building can be stated as,

$$V = \frac{G_p \cdot 10^6}{G_{c,in} - G_{c,out}} \quad (1)$$

where V is the ventilation rate, m³/s; G_p is the amount of injected tracer gas or produced gas inside the building space, m³/s; and $G_{c, in}$ and $G_{c, out}$ are the gas concentration measured inside and outside the buildings respectively, ppm. By using CO₂ produced by the animals, G_p will be computed based on a heat/CO₂ production model, and $G_{c, in}$ and $G_{c, out}$ will be the measured CO₂ values in and out of the ventilated space. The description of balance is true when the room air is fully mixed with the supply inlet air and the CO₂ production model accurate.

However, a crucial challenge in practice for such estimation is choosing the locations for the concentration measurements and the numbers of the measurement locations. A ventilated room space is hardly perfect mixed, especially for a naturally ventilated open building. Variation of wind speed, direction and turbulence scale makes the situation more complicated than a mechanical ventilation process.

Another challenge could be to validate the CO₂ production model and make necessary correction under varied conditions that may influence the accuracy of the model.

In this paper, the discussions will be focused on cattle and open buildings.

3. ANIMAL HEAT AND CARBON DIOXIDE PRODUCTION

3.1 Heat and CO₂ production models

The animal carbon dioxide production is closely related to the animal total heat production, where the total heat production for cattle at 20 °C can be calculated from the following equations, (CIGR, 2002), for cattle:

3.1.1 Calves

$$\Phi_{tot} = 6.44m^{0.70} + \left[\frac{13.3Y_2(6.28 + 0.0188m)}{1 - 0.3Y_2} \right], W \quad (2)$$

Y_2 = daily gain, normally 0.5 kg/day

m = body mass, kg.

3.1.2 Veal calves, beef cattle

$$\Phi_{tot} = 7.64m^{0.69} + Y_2 \left[\frac{23}{M} - 1 \right] \left[\frac{57.27 + 0.302m}{1 - 0.171Y_2} \right], W \quad (3)$$

Y_2 = daily gain, 0.7-1.1 kg/day

M = Energy content MJ/kg dry matter

($M = 10$ MJ/kg_{dry matter} for roughage)

($M = 11-12$ MJ/kg_{dry matter} for concentrates)

3.1.3 Heifers

$$\Phi_{tot} = 7.64m^{0.69} + Y_2 \left[\frac{23}{M} - 1 \right] \left[\frac{57.27 + 0.302m}{1 - 0.171Y_2} \right] + 1.6 \times 10^{-5} p^3, W \quad (4)$$

Y_2 = daily gain, 0.6 kg/day.

p = Days of pregnancy

3.1.4 Cows

$$\Phi_{tot} = 5.6 m^{0.75} + 22Y_1 + 1.6 \times 10^{-5} p^3, W \quad (5)$$

Y_1 = milk production, kg/day

p = Days of pregnancy.

When expressed per hpu (1000 W in total heat at 20°C), the following equations for total heat production at temperatures outside 20 °C can be derived:

$$\text{Cattle:} \quad \Phi_{tot} = 1000 + 4 \times (20 - t), W \quad (6)$$

The total heat production for cattle, pigs and poultry is shown in Figure 1.

As shown in the Figure 1, the animal heat production for big animals as cattle is less sensitive to the temperature as for small animals, like poultry.

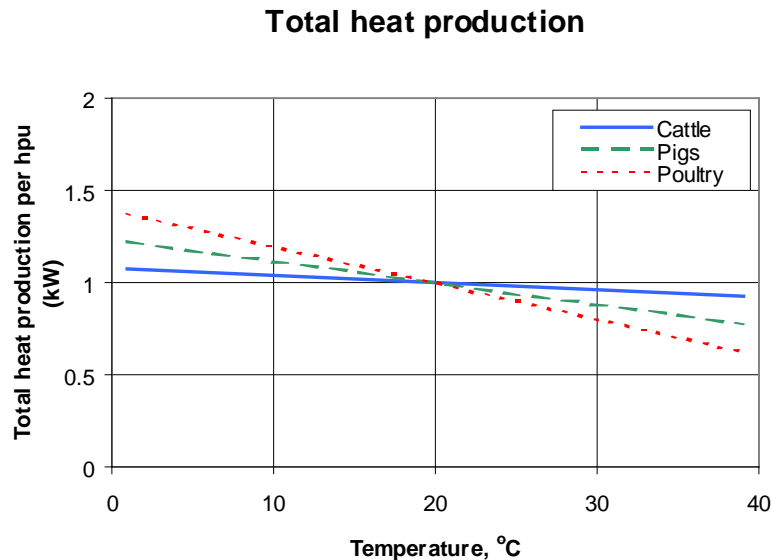


Figure 1. Total heat according in respect to indoor temperature.

3.2 Animal Carbon dioxide production

The relation between animal heat production and the carbon dioxide can be derived from the basic equation set up by Brouwer (1965), based on oxygen consumption (O_2 , l), carbon dioxide production (CO_2 , l), urinary nitrogen (N, g) and methane production (CH_4 , l):

$$HE_{kJ} = 16.18 O_2 + 5.02 CO_2 - 5.99 N - 2.17 CH_4 \quad (kJ) \quad (7)$$

By using the Brouwer's equation (Eq 5), estimations of heat production can be carried out under laboratory conditions in respiration chambers. However, under practical conditions and full scale production, only the CO_2 production can be measured. As shown by Pedersen et al. 2008, the carbon dioxide production in relation to the total heat production can with approximation be simplified, taking into account the RQ (the ratio between the CO_2 production and O_2 consumption during respiration)

The interest for using the animal carbon dioxide (CO_2) production to estimate the air exchange rate from CO_2 balances in the house was awakened already in the seventies. In the period 1977-84, the literature on animal heat and moisture production was examined by a CIGR (Internationale Commission du Génie Rural) working group, and the outcome was published by CIGR (1984). In this report, the CO_2 production was determined as $0.163 \text{ m}^3\text{h}^{-1}\text{hpu}^{-1}$. In 1994, the CO_2 production was revised and it was adjusted to the range between 0.17 and $0.20 \text{ m}^3\text{h}^{-1}\text{hpu}^{-1}$ depending on production level (Ouwerkerk and Pedersen, 1994). Today the production level for e.g. broilers, growing pigs and dairy cattle is much higher than fifty years ago, which can partly explain the increase over time in CO_2 production per hpu.

3.3 Carbon dioxide production measured in respiration chambers

Table 1 shows the CO₂ production from different categories of cattle based on experiments performed in respiration chambers in Denmark and the Netherlands.

Table 1 CO₂ production (University of Wageningen, the Netherlands)

Animal	Year	N° Animals	Temp °C	LW Kg	CO ₂ l d ⁻¹	RQ	HE kJ d ⁻¹	CO ₂ production m ³ h ⁻¹ hpu ⁻¹
Veal calve	¹)2006	1	18	145	1072	0.88	25042	154
Veal calve	²)2006	1	18	152	1174	0.86	28033	151
Cows	³)2007	2	18	584	6148	1.06	123802	179
Cows	⁴)2007	2	16	560	6049	1.02	125100	174
Cows	⁵)	2	16	553	5856	1.08	116225	181

¹) Borne, J.J.G.C. van den et al., 2006a. ²) Borne, J.J.G.C. van den, 2006b. ³) Straalen, W.M. et al., 2007.

⁴) Knegsel, A.T.M. et al., 2007. ⁵) Unpublished.

Figure 2 shows the relation between RQ and the CO₂ production measured in respiration chambers in the Netherlands for cattle from respiration chambers. The figure shows that the CO₂ production increases linear with the increase in RQ. These results correspond well with the general findings by Ouwerkerk and Pedersen, (1994), based on a literature review, where it was concluded that the CO₂ production increases from 0.17 to 0.20 m³ h⁻¹hpu⁻¹, when RQ increases from 1.0 to 1.2.

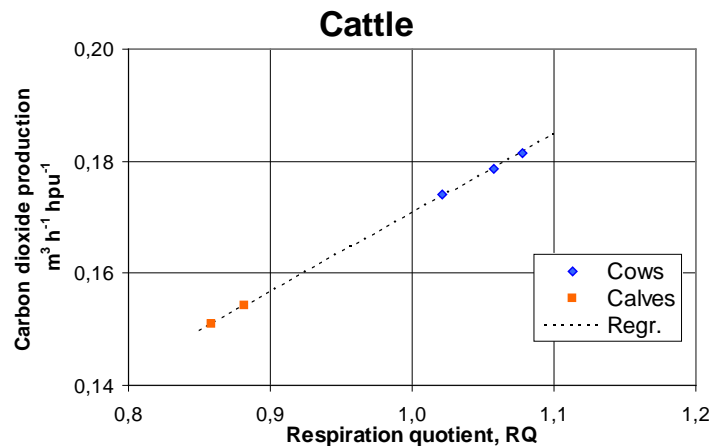


Figure 2. Relation between the CO₂ production and the RQ for cattle, measured in respiration chambers in NL.

As the CO₂ production per hpu increases with increasing respiration quotient and the respiration quotient increases with body mass, the CO₂ production per hpu also increases with body mass, as shown in Figure 2.

In respiration chambers there is no or very limited CO₂ contribution from manure; unlike in animal houses, where a certain CO₂ contribution from manure handling may be

foreseen. Therefore, it is necessary to make an adjustment of data from respiration chambers, when used in full scale animal buildings as basis for estimation of ventilation flow.

3.4. Provisional recommendations for animal CO₂ production in respect to species and body mass

Figure 2 also show that a lower CO₂ production per hpu may be expected from calves than from dairy cows without consideration for contribution of CO₂ from manure handling systems. A guideline for the total CO₂ production in traditional animal houses, excl. deep litter, is presented in Table 2 (Pedersen et al. 2008).

Table 2. Provisional values of CO₂ production in livestock houses in animal and house level.

	CO ₂ production, m ³ h ⁻¹ hpu ⁻¹	
	Animal level	House level *)
Calves	0.155	0.170
Dairy cows	0.180	0.200

*) Including CO₂ production from manure (excl. deep litter and indoor manure storage over a time period longer than 3 weeks).

4. MEASUREMENTS OF CO₂ CONCENTRATIONS

Measurements were carried out in selected free-stall dairy cattle buildings with different type floors and different manure handling systems. Figure 3 shows an example of the measurement section and sensor positions in a building. All buildings were naturally ventilated with side-wall and ridge openings. The selected buildings were newer type dairy cattle buildings with a milking centre at one end and the animal occupied area in the rest of the building (Zhang *et al.* 2005).

Figure 3. Measurement section and sensor positions.

In order to achieve reliable averages of the emission data and the variations in concentration, air exchange rate and emission, air sampling was done for a minimum period of three days was

selected with five days as a preference. The ventilation flows were in the range of 600 to 2500 m³ h⁻¹hpu⁻¹.

5. COMPARING OF RESULTS USING CO₂ MODEL AND OTHER TRACER GASES

Estimation of the air exchange rates plays a key role in determining the emission rates of aerial pollutants from animal buildings. Although a temperature difference provides a buoyant force that induces ventilation in livestock buildings, wind effects contributes more to the air exchange as wind speed increases. A ventilation opening may act as an inlet during one period and as an outlet during another period due to variations of wind direction. In some cases, wall or ridge openings may act as an inlet at one end of the building and as an outlet at the other. All these factors add to the uncertainties of determination of the air exchange rates in addition to imperfect mixing.

When the tracer gas SF₆ was prohibited, the model aided CO₂ balance method was used as the primary method to estimate the air exchange rate assuming that the CO₂ produced in the building is predicted accurately by the CO₂ model (Strøm, 1978; CIGR, 1984). Consequently, the air exchange rate can be determined by mass balance of CO₂. However, due to the imperfect mixing and non-uniformly wind pressure distribution, there is still uncertainty in the method, but at this point it was deemed the best method available. The estimated air exchange based on tracer gas and CO₂ model are shown in Figure 4.

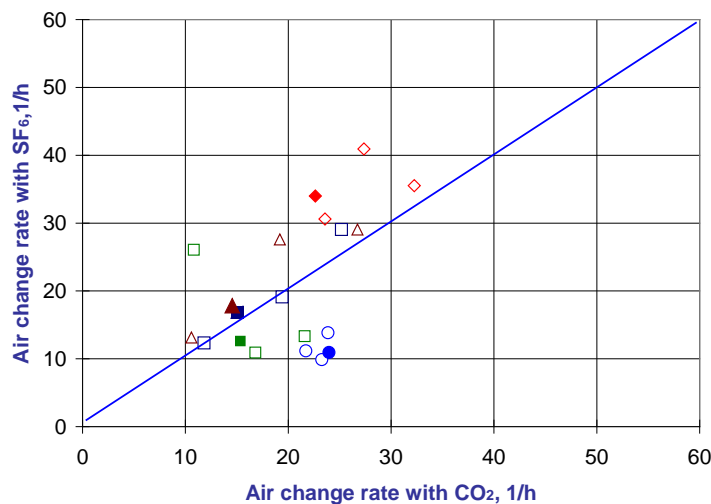


Figure 4. Air exchange rates measured by tracer gas versus estimated by CO₂ production modeling method for buildings A, B, C, D and E as one day's average (□, □, △, ○, ◇), and as three day's average (■, ■, ▲, ●, ◆) respectively.

6. ERROR SOURCES BY CALCULATING VENTILATION FLOW BASED ON CO₂ MEASUREMENTS

As shown in Eqn. 1, the carbon dioxide method is based on the animal heat and carbon dioxide production, where the factor for carbon dioxide production per hpu is shown in Table 2 for calves and dairy cows on animal and house level.

Calculating the total ventilation flow, based on the animal carbon dioxide production on house level implies the following parameters:

1. Animal total heat production in hpu per animal
2. Carbon dioxide production per hpu
3. Diurnal variation in animal heat production.
4. Instrumental errors in carbon dioxide measurement
5. Error in representative placing of carbon dioxide sensors.

For natural open buildings, the ventilation flow is very high, and the carbon dioxide concentration in the building is correspondingly low. Furthermore carbon dioxide concentration is very uneven distributed over the ventilation openings from time to time, due to changing wind direction and speed, causing large risk for wrong calculations of the ventilation flow, because it is difficult to select representative sensor locations.

As basis for estimation of the uncertainty of estimated total ventilation flow in houses for dairy cattle, the following errors may be foreseen:

- | | |
|---|------------|
| 1. hpu per animal (CIGR 2002 eqn.) | +/- 10 % |
| 2. CO ₂ production, 0.200 m ³ h ⁻¹ hpu ⁻¹ . | +/- 10 % |
| 3. Diurnal variation in CO ₂ production per hpu | +/- 20 % |
| 4. CO ₂ measurements (CO ₂ in – CO ₂ out) | +/- 40 ppm |
| 5. Error due to representative location of CO ₂ sensors. | +/- 40 % |

For traditional closed buildings with well defined outlets, the average carbon dioxide concentration can simply be measured in the outlets. However, the challenge for identification/allocation of air inlets and outlets in an open building may result in large errors for measurements of the exhaust air concentrations, - and this is also a challenge for using other tracer gases as e.g. SF₆.

By using carbon dioxide measurements for estimation of ventilation flow all five parameters 1 to 5 should be taken into account, while for artificial tracer gases only 4 and 5 should be taken into account.

The total error for a number of factors can be calculated by Eqn. 8

$$\text{Total error} = (a_1^2/A_1^2 + a_2^2/A_2^2 + \dots + a_n^2/A_n^2)^{0.5} \quad (8)$$

where $a_1, a_2 \dots a_n$, are the assumed errors of the parameters $A_1, A_2 \dots A_n$

Figure 5 shows the measuring error in per cent in respect to the ventilation flow per hpu (1000W total heat production at 20 °C), for an animal house with a diurnal variation in carbon dioxide production of +/- 20 %, taken into account errors on parameter 1 to 4.

The figure shows that the error is increasing with increased ventilation flow due to uncertainty in measuring CO₂ differences and it is highest if not taken into account the diurnal variation in animal carbon dioxide production. For confined buildings, with low ventilation flow per hpu, and a typical diurnal variation in carbon dioxide production of +20 % in the daytime and -20% in the night-time, the error increases by about 70 %, if

not taking into account the diurnal variation. The figure also shows that the impact of including animal activity is of minor importance for open animal houses with high ventilation flow, where errors on CO₂ measurements are dominating.

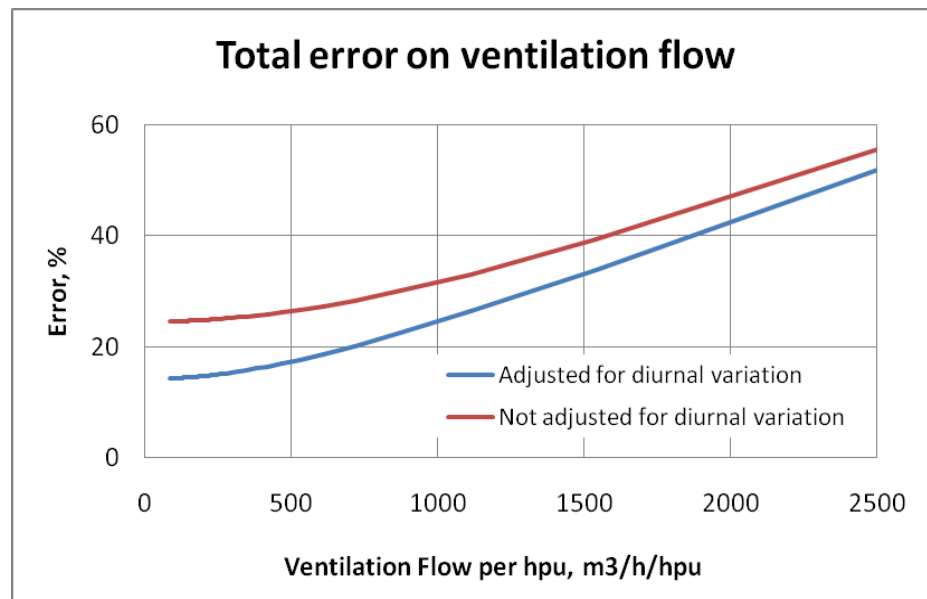


Figure 5 Total errors in ventilation flow, excl. errors due to non representative placing of sensors

The biggest challenge in using tracer gases for estimation of ventilation flow is to decide where the carbon dioxide concentration should be placed. The potential error due to wrong sensor placing is increasing progressively with the size of wall and roof openings. If we assume that the error in selection of representative measuring points for a ventilation flow of 1500 m³/h per hpu (CO₂ difference 130 ppm) is 40%, the error in estimated flow will be about +/- 750 m³h⁻¹hpu⁻¹ and the inclusion of errors due to the parameters 1 to 4 will be of minor importance.

The big challenge for the future is to make recommendations for how to organize the sensor placing for minimizing the uncertainty in the calculated ventilation flow.

7. CONCLUSION

- The animal CO₂ production depends on the specie, the body mass and the feeding level, and ranges from about 0.16 to 0.21 m³h⁻¹hpu⁻¹
- The animal CO₂ production is closely related to the oxygen consumption, expressed by the respiratory quotient RQ. CO₂ production is about 0.16 m³h⁻¹hpu⁻¹ at a RQ of 0.9 increasing to around 0.20 m³h⁻¹hpu⁻¹, at a RQ of 1.2.
- The animal CO₂ production under normal farm conditions has normally a diurnal variation of +/- 20%.
- Estimation of ventilation airflow on hourly basis for mechanically ventilated buildings can be improved considerable by an adjustment for the diurnal variation in the CO₂

production. For open buildings with high ventilation flow rate, the dominating error source is due to the challenges in selecting representative placing, therefore the adjustment for diurnal variation in CO₂ production is of minor importance.

- It is assumed that the error in estimated ventilation flow for open buildings is in the range of +/- 50 %. The challenge remains for the future to make recommendations for how to organize the sensor placing for minimizing the uncertainty in the calculated ventilation flow.

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