Carbon Dioxide Production in Animal Houses: A literature review

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ABSTRACT

This article deals with carbon dioxide production from farm animals; more specifically, it addresses the possibilities of using the measured carbon dioxide concentration in animal houses as basis for estimation of ventilation flow (as the ventilation flow is a key parameter of aerial emissions from animal houses). The investigations include measurements in respiration chambers and in animal houses, mainly for growing pigs and broilers.

Over the last decade a fixed carbon dioxide production of 185 litres per hour per heat production unit, hpu (i.e. 1000 W of the total animal heat production at 20 ^{o}C) has often been used. The article shows that the carbon dioxide production per hpu increases with increasing respiration quotient. As the respiration quotient increases with body mass for growing animals, the carbon dioxide production per heat production unit also increases with increased body mass. The carbon dioxide production is e.g. less than 185 litres per hour per hpu for weaners and broilers and higher for growing finishing pigs and cows.

The analyses show that the measured carbon dioxide production is higher in full scale animal houses than measured in respiration chambers, due to differences in manure handling. In respiration chambers there is none or very limited carbon dioxide contribution from manure; unlike in animal houses, where a certain carbon dioxide contribution from manure handling may be foreseen. Therefore, it is necessary to make a correction of data from respiration chambers, when used in full scale animal buildings as basis for estimation of ventilation flow. Based on the data reviewed in this study, we recommend adding 10% carbon dioxide production to the laboratory based carbon dioxide production for animal houses with slatted or solid floors, provided that indoor manure cellars are emptied regularly in a four weeks interval. Due to a high and variable carbon dioxide production in deep straw litter houses and houses with indoor storage of manure longer than four weeks, we do not recommend to calculate the ventilation flow based on the carbon dioxide concentration for these houses.

Keywords: Carbon dioxide, ventilation flow, animal heat production, balance equations, farm buildings

1. BACKGROUND

Ventilation of animal houses should be based on maintaining desired thermal conditions and air quality. This requires no build up of heat and/or gases in the inside air. At equilibrium (steady state) this means that emission of a gas of must equal the amount in the outgoing ventilated air. Estimation of the gas emission needs knowledge on both the air exchange to the environment and the gas concentration in the animal house. Precise air exchange measurements can be performed by measuring nozzles or measuring fans installed in the outlets of the animal house, but these are time-consuming and expensive methods and they are to some extends limited to mechanically ventilated animal houses. Therefore, there is a big interest in finding alternative methods for estimating the ventilation flow in full scale livestock buildings. One possibility is e.g. to use tracer gases (Freon 134a), where a correlation of 0.89 was found (Müller, H-J et al. 2006) in respect to wheel anemometer measurements. Another possibility is to estimate the air exchange rate by performing a carbon dioxide (CO_2) balance in the house. In the CO_2 balance, an accurate estimation of the CO_2 production in the building is crucial. The total CO_2 production includes CO_2 produced by the animals and CO_2 emitted from the manure. CO_2 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. slatted houses with regular emptying of manure pits) the CO_2 production from the manure handling system is small compared to the CO_2 production from animals. However, in animal houses with deep litter (i.e animal houses where the depth of the litter is > 0.5m), the CO_2 production from the deep litter can be considerable (Jeppsson 2000, 2002)

The structure of this paper is as follows. First, we present a theoretical approach for calculating the animals CO_2 emission based on indirect calorimetric measurements (RQ method). Next, we provide an overview of research studies dealing with the CO_2 production at house level and we present a summary of published data on animal CO_2 production measured in respiration chambers. We compare the results of the different studies and we discuss the current state of knowledge of the CO_2 production in animal houses, concluding by providing some recommendations. Third, we discuss the importance of considering the diurnal variation of CO_2 production. Finally, we present the equations for calculating the ventilation flow based on measured CO_2 production.

2. A THEORETICAL APPROACH: THE RQ METHOD

An equation for estimating animal heat production on diurnal basis (HE, kJ) was 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), as follows (Eq 1):

$$HE_{kJ} = 16.18\ O_2 + 5.02\ CO_2 - 5.99\ N - 2.17\ CH_4 \quad (kJ) \qquad (1)$$

By using the Brouwer's equation (Eq 1), precise estimations of heat production can be carried out under laboratory conditions in the respiration chambers. However, under practical conditions and full scale production, only the CO_2 production can be measured. An estimation of RQ (the ratio between the CO_2 production and O_2 consumption during respiration) can be made based on the nutrient composition of the diet (protein, lipids and carbohydrates) and from the composition of the gained tissues in the animal (protein and fat) (see Brouwer, 1965). If animals are fed close to maintenance the RQ will be low, but it will increase with higher feed intake, e.g. the RQ value for pregnant sows with low feed intake is lower than for lactating sows. The RQ varies between 0.9 and 1.2 (Van Ouwerkerk and Pedersen, 1994).
Eq. 1 can be modified by substituting the oxygen consumption O_2 in Eq. 1 by the term CO_2/RQ and expressing the HE in terms of kW (as it is commonly used for calculations of animal heat production in relation to heating and ventilating animal houses), resulting in Eq. 2:

$$HE_{kW} = \frac{1}{3.6} \cdot \left(16.18 \cdot \frac{CO_2^{'}}{RQ} + 5.02 \cdot CO_2^{'} - 5.99 \cdot N^{'} + 2.17 \cdot CH_4^{'} \right) \text{, kW} \qquad (2)$$

where $CO_2^{'}$ and $CH_4^{'}$ are expressed in terms of m^3/h, and $N^{'}$ in g/h.

For one hpu (where 1 hpu is equivalent to 1000 W of total heat production at 20ºC), Eq2 can be transformed to:

$$RQ = \frac{16.18 \cdot CO_2^{'}}{3.6 - 5.02 \cdot CO_2^{'} + 5.99 \cdot N^{'} + 2.17 \cdot CH_4^{'}} \qquad (3)$$

According to the literature (CIGR, 2002, the CO_2 production per hpu has over the last decade often been set to 0.185 $m^3h^{-1}hpu^{-1}$. In the case of fattening pigs, a urinary nitrogen production of 0.010 kg h^{-1} hpu^{-1} and a CH_4 production of $0.24x10^{-3}$ kg h^{-1} hpu^{-1} can also be obtained from the literature (Blanes-Vidal et al., 2008). Using those data in Eq 3 we get:

$$RQ = \frac{16.18 \cdot 0.185}{3.6 - 5.02 \cdot 0.185 + 5.99 \cdot 0.010 + 2.17 \cdot 0.00024} = 1.096 \qquad (4)$$

Solving Eq. 4, results in a CO_2 production of 0.185 $m^3h^{-1}hpu^{-1}$ corresponding to an RQ of about 1.1, which is a typical value of RQ for fattening pigs (Noblet et al., 1999; Van Ouwerkerk and Pedersen, 1994).

3. OVERVIEW OF STUDIES ON CARBON DIOXIDE PRODUCTION AT HOUSE LEVEL

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 awaked in the seventies. In the period 1977-84, the literature on animal heat and moisture production was examined by the CIGR (Internationale Commision du Génie Rural) working group, and the outcome was published in by CIGR (1984). In this report, the CO_2 production was determined as 0.163 $m^3h^{-1}hpu^{-1}$. In 1994, the CO_2 production was revised and it was adjusted to the range between 0.17 and 0.20 $m^3h^{-1}hpu^{-1}$ (Ouwerkerk and Pedersen, 1994). In that work it was also stressed that the animal activity is an important factor to take into account when calculating CO_2 balances over periods shorter than 24 hrs. Later studies have confirmed the necessity of taking the animal activity into account. One of those studies was a Swedish investigation with layers (Wachenfelt et al., 2001) that showed that the CO_2 production during the night periods was only 66% of the production during day periods.

Comprehensive investigations on emission from animal houses were performed from 1992-1996 (EU project No. PL900703), including animal houses in Great Britain, Netherlands, Germany and Denmark, where information on the ventilation flow was needed. Due to the big number of animal houses included in the investigation, it was not possible to provide the houses with direct measurements of ventilation flow by nozzles or measuring fans. Therefore the heat, moisture and CO_2 balances in cattle, pigs and poultry houses were calculated in order to make an indirect calculation of the ventilation flow. The procedure was to formulate three balance equations for each house; a temperature balance, a moisture balance and a CO_2 balance, each expressing the ventilation flow. These three equations must theoretically result in the same ventilation flow for a certain house. The equations were based on data for animal heat and moisture production from CIGR (1984). Firstly, the temperature balance and the moisture balance equation were brought to give the same ventilation flow by adjusting the animal latent and sensible heat for evaporation of water from feed and manure. Secondly, that ventilation flow was used to calculate the CO_2 production by the CO_2 balance equation. The results showed that the CO_2 production on diurnal basis (average of 24 h period) was 0.185 $m^3h^{-1}hpu^{-1}$ for dairy cows, growing pigs and layers (Pedersen et al, 1998). That is about 13% higher than that estimated by CIGR (1984).

Danish measurements of broiler heat and moisture production showed a CO_2 production of 0.182 m^3 $m^3h^{-1}hpu^{-1}$ (Pedersen and Thomsen, 2000), which was in good agreement with 0.185 $m^3h^{-1}hpu^{-1}$. Furthermore, a later Danish investigation with fattening pigs showed a CO_2 production of 0.185 $m^3h^{-1}hpu^{-1}$ (Sousa and Pedersen, 2003). However, Blanes and Pedersen (2005), found that the CO_2 production was 0.201 $m^3h^{-1}hpu^{-1}$. A Ph.D study (Haeussermann, 2006, Haeussermann et al., 2007ab) resulted in a CO_2 production for growing pigs of 0.233 $m^3h^{-1}hpu^{-1}$ between day 10 and 28 in the growing finishing house, averaged over four growing periods in a full scale experimental house (Table 1). It increases by about 18% in respect of the above mentioned value during the ongoing growing days. The high CO_2 production compared to the other referred experiments is

explained mainly by the accumulated amount of manure, which was stored indoor until the end of each fattening period. Likewise, high performance of the pigs, listed in Table 1 for growing finishing pigs, influenced CO_2 production due to an increased RQ.
In Belgium, a number of measurements were carried out over a decade under different production conditions for pigs (Nicks et al., 2003, 2004a,b, 2005; Philippe et al., 2006, 2007). Based on the measured CO_2 production and the total heat production calculated in accordance with CIGR (2002), the CO_2 production is expressed in terms of $m^3\ h^{-1}\ hpu^{-1}$ as shown in Table 1. The results show a big variation among the different experiments and it also shows that the CO_2 production per hpu is much lower for weaning pigs than for growing finishing pigs.

Table 1. Measured CO_2 production in animal houses from Belgium and German research studies in full scale experimental pig houses

Livestock	Bedding Type	Live weight Kg	Temp °C	Daily gain kg/day	CO_2 production $m^3\ h^{-1}\ hpu^{-1}$	Reference
Weaning Pigs	Straw	12.9	23.7	0.39	0.173	Nicks et al. (2003)
	Sawdust	13.0	23.0	0.40	0.178	
	Slatted	12.3	26.4	0.39	0.122	Nicks et al. (2004a)
	Straw	12.3	23.9	0.39	0.130	
	Slatted	11.8	24.2	0.39	0.137	Nicks et al. (2005)
	Sawdust	11.8	22.6	0.39	0.168	
Growing finishing Pigs	Straw	67.0	20.0	0.76	0.151	Nicks et al. (2004b)
	Sawdust	68.6	19.1	0.79	0.149	
	Straw	70.2	21.8	0.74	0.181	Philippe et al.(2006)
	Straw	67.9	21.2	0.70	0.178	
	Slatted	67.8	20.5	0.73	0.202	Philippe et al.(2007)
	Straw	67.0	20.6	0.72	0.230	
Growing finishing Pigs	Slatted	43.0	21.5	0.84	0,233	Haeussermann (2006)
		62.0	21.5	0.91	0,266	
		80.0	19.9	0.83	0,282	
		97.0	18,9	0.73	0,282	

Table 2 shows results from different sources, including cattle, pigs and poultry.

Table 2. CO_2 production in animal houses, different sources.

Livestock	Experimental setup	CO_2 production, $m^3\ h^{-1}\ hpu^{-1}$	Reference
Cattle and pigs	Commercial farm	0.17 - 0.20	Van Ouwerkerk and Pedersen (1994)
Cattle, pigs and poultry	Commercial farm	0.185	Pedersen et al. (1998)
Pigs			
Fattening pigs	Commercial farm	0.173 (animals) 0.232 (total)[1)]	Ni et al. (1999)
Fattening pigs	Full scale experimental farm	0.185	Sousa and Pedersen (2004)
Fattening pigs	Full scale experimental farm	0.201	Blanes and Pedersen (2005)
Fattening pigs	Full scale experimental farm	0.178 - 0.325[2)]	Haeussermann (2006)
Poultry			
Broilers in straw bedding	Experimental farm	0.182	Pedersen and Gaardbo-Thomsen (2000)
Laying hens in cages	Commercial farm	0.137 (light) 0.191 (dark)	Li et al. (2006)

[1)] Partial slatted floor. [2)] Depending on age of pigs, pig performance and manure amount

4. CARBON DIOXIDE PRODUCTION MEASURED IN RESPIRATION CHAMBERS

Table 3, 4 and 5 shows the CO_2 production from different types of animals (e.g. different species and production conditions) based on experiments performed in respiration chambers in Denmark and the Netherlands.

Table 3. CO_2 production (University of Copenhagen, Denmark).

Animal	Year	N° animals	Temp	LW	CO_2	RQ	HE	CO_2 production
			°C	Kg	$l\ d^{-1}$		$kJ\ d^{-1}$	$m^3h^{-1}hpu^{-1}$
Pigs	[1)]2001	54	20	30.7	514	1.05	10486	0.177
Pigs	[2)]2004	32	18	54.6	911	1.10	17855	0,184
Sheeps	[3)]2004	27	16-18	77.8	471	0.92	10620	0.160
Broilers 1.week 2.week 3.week	[4)]2004	16	30-28 28-24 24-20	0.074 0.172 0.334	4.26 9.84 17.8	0.99 0.89 0.93	90.8 230 399	0.169 0.154 0.161
Old investigations								
Laying hens	[5)]1985	204	17-21	1.53-1.97	35.2-43.5	0.81-1.01	767-900	0.170
Pigs	[6)]1984	28	(18)	20 120	343 977	1.00 1.00	6986 20419	0.170 0.196

[1]Chwalibog et al. 2004, [2]Hansen et al. 2007, [3]Kiani et al. 2007. [4]Chwalibog et al. 2004, [5]Chwalibog,1985, [6]Thorbek et al.,1984.

Table 4. CO_2 production (University of Aarhus, Denmark)

Animal	Year	Nº animals	Temp	LW	CO_2	RQ	HE	CO_2 production
			ºC	kg	$l\ d^{-1}$		$kJ\ d^{-1}$	$m^3h^{-1}hpu^{-1}$
Piglets	[1)]2007	12	27	4.9	94.3	0.86	2240	0.152
Growing pigs	[2)]1996	12	13	77	1049	1.08	20600	0.183
	[2)]1996	12	23	86	956	1.16	18140	0.190
	[3)]1996	56	21	58	676	1.02	14040	0.173
	[4)]1997	86	20	92	826	1.01	17440	0.171
	[5)]1998	30	20	60	707	1.04	14440	0.176
	[6)]2001	27	20	63	742	1.04	15200	0.176
	[7)]2004	32	20	51	824	1.17	16440	0.180
	[8)]2007	16	19	90	856	1.11	16610	0.186
Sows, pregnant	[9)]2001	12	17	288	1350	1.17	30080	0.162
	[10)]2001	36	20	227	1125	0.95	24180	0.167
	[11)]2002	34	20	201	1173	0.67	24840	0.170
Sows, lactating	[12)]2004	24	21	206 +43 (pigs)	1762	1.01	36930	0.172
Sows, dry	[13)]2007	18	18	208	1077	0.96	23380	0.166
Chickens (Broilers)	[14)]1990	120	22	1.02	37.9	1.04	780	0.175
	[15)]1996	162	24	0.91	34.3	0.99	730	0.169
	[16)]2001	24	23	0.88	31.1	0.92	700	0.160
	[17)]2006	39	25	0.83	28.7	0.92	640	0.161

[1)]Theil et al., 2007, [2)]Jørgensen et al., 1996c, [3)]Jørgensen et al., 1996a, [4)]Jørgensen et al., 1997, [5)]Jørgensen, 1998, [6)]Jørgensen et al., 2001, [7)]Wang et al., 2004., [8)]Jørgensen et al., 2007, [9)]Olesen et al., 2001, [10)]Jørgensen et al., 2001, [11)]Theil et al., 2002, [12)]Theil et al., 2004, [13)]Jørgensen et al., 2007, [14)]Jørgensen et al., 1990, [15)]Jørgensen et al., 1996b, [16)]Zhao et al., 2001, [17)]Zheng et al, 2006.

Table 5 CO_2 production (University of Wageningen, the Netherlands)

Animal	Year	Nº animals	Temp °C	LW kg	CO_2 $l\ d^{-1}$	RQ	HE $kJ\ d^{-1}$	CO_2 production $m^3h^{-1}hpu^{-1}$
Veal calve	[1] 2006	1	18	145	1072	0.88	25042	0.154
Veal calve	[2] 2006	1	18	152	1174	0.86	28033	0.151
Cows	[3] 2007	2	18	584	6148	1.06	123802	0.179
Cows	[4] 2007	2	16	560	6049	1.02	125100	0.174
Cows	[5]	2	16	553	5856	1.08	116225	0.181
Piglet	[6]	3	25	10.6	169	0.98	3628	0.168
Piglet	[7]	2	22	11.9	188	0.97	4083	0.166
Piglet	[8]	5	20	28	394	0.98	8486	0.167
Growing pigs	[9] 2001	1	20	53	580	0.97	12631	0.165
Growing pigs	[10]	7	20	46	533	0.99	11415	0.168
Growing pigs	[11]	14	20	51	581	0.99	12416	0.169
Growing pigs	[12] 2005	10	22	66	792	1.05	16117	0.177
Growing pigs	[13]	14	20	34	438	0.99	9346	0.169
Growing pigs	[14] 2008	12	20	44	588	0.99	12513	0.169
Sow	[15] 2001	6	20	229	1196	0.96	26112	0.165
Sow	[16] 2004	3	20	172	924	0.94	20511	0.162
Broilers	[17]	39	18	1.7	58	0.95	1275	0.165
Layers	[18] 2000	6	21	2.4	43	0.88	1012	0.155
Layers	[19] 2006	8	22	1.6	28	0.97	613	0.164
Young layer	[20]	10	21	1.0	32	0.94	715	0.161
Young layer	[21] 2002	10	21	0.6	22	0.96	486	0.162

[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, 6, 7 and 8] Unpublished. [9] Gerrits, W.J.J. et al., 2001. [10 and 11] Unpublished. [12] Huynh Thi Thanh Thuy et al., 2005. [13] Unpublished. [14] Bolhuis, J. E.et al., Accepted for publication. [15] Rijnen-MMJA et al. 2001.[16] Geverink, N.A. et al, 2004. [17] Unpublished. [18] Mashaly-MM et al., 2000. [19] Eerden, E. van et al., 2006. [20] Unpublihed. [21] Parmentier et al., 2002.

5. RELATION BETWEEN RQ AND THE CO_2 PRODUCTION, BASED ON DATA FROM RESPIRATION CHAMBERS

Figures 1, 2 and 3 shows the relation between RQ and the CO_2 production measured in respiration chambers in Denmark (DK) and the Netherlands (NL) for cattle, pigs and poultry from respiration chambers (based on Tables 3, 4 and 5). The figures show that the

CO_2 production increases nearly 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 CO_2 production increases from 0.17 to 0.20 $m^3\ h^{-1} hpu^{-1}$, when RQ increases from 1.0 to 1.2.

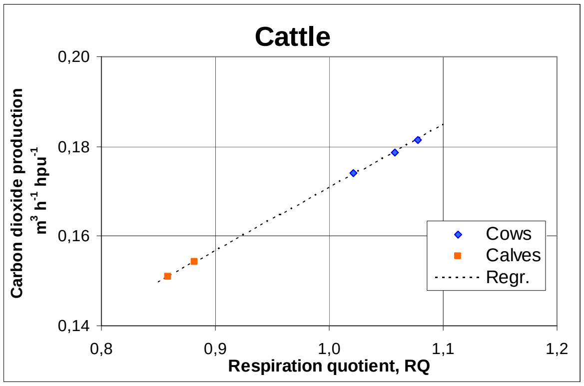

Figure 1. Relation between the CO_2 production and the RQ for cattle (Measured in respiration chambers in DK and NL).

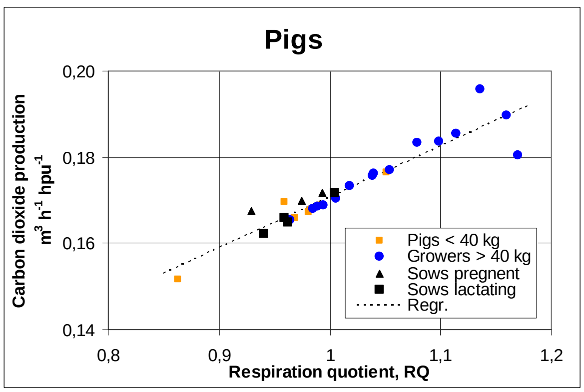

Figure 2. Relation between the CO_2 production and the RQ for pigs (Measured in respiration chambers in DK and NL).

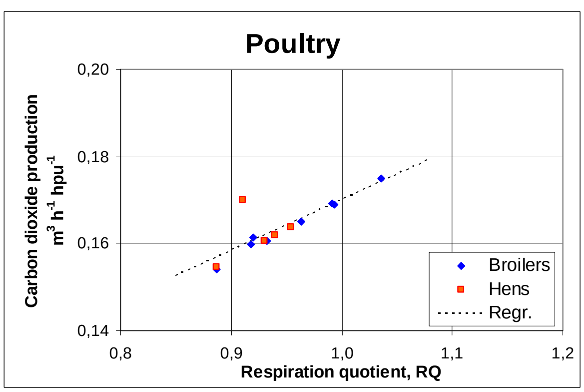

Figure 3. Relation between the CO_2 production and the RQ for poultry (Measured in respiration chambers in DK and NL).

As the CO_2 production per heat production unit increases with increasing respiration quotient and the respiration quotient increases with body mass, the CO_2 production per heat production unit also increases with body mass, as shown in Figure 4.
Based on Tables 1 to 5 on data from measurements in respiration chambers and full scale production facilities, it is possible to make a re-examination of the present factor of 185 litre CO_2 m^3 h^{-1} hpu^{-1}.
In respiration chambers there is no or very limited CO_2 contribution from manure; unlike in animal houses, where a certain CO_2 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. Measurements in traditional pig houses over the last decade (Table 1 and 2) have shown a higher CO_2 for growing pigs than demonstrated in Figure 4. In Ouwerkerk and Pedersen (1994), the CO_2 contribution from the manure system is estimated to be 4%. Based on Table 1 to 5, it seems likely that the contribution from the manure system is higher and probably around 10% and above. The dotted line in Figure 4, represents such an empiric adjustment of the animal CO_2 production into the CO_2 production at house level. For animal houses with regularly removal of manure and good management, the contribution will probably be lower than 10%. Nevertheless, housings where manure is stored indoors over a considerable time period (more than 3 weeks) will result in a high CO_2 contribution from the manure, which can be up to a 35% (Ni et al., 1999b). Information about manure handling has to be included when estimating ventilation flow from such housings based on CO_2 production in order to get accurate values.

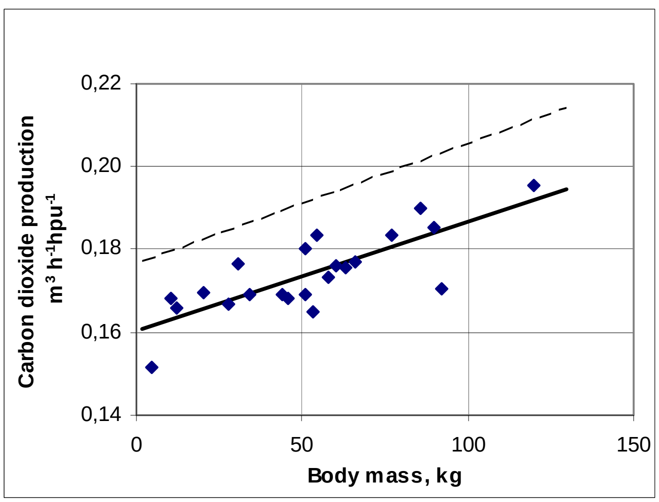

Figure 4. The CO_2 production in relation to body mass, measured in respiration chambers for growing pigs and estimated (dotted line) at house level.

Likewise, the adjustment of the total CO_2 production for animal houses with deep litter will not be discussed in this paper, because ventilation flow based on CO_2 production will always be uncertain for that type of production facilities, due to the important contribution of the litter to the total CO_2 production at house level, and the fact that CO_2 production from litter is very difficult to estimate in full scale facilities under normal production conditions. In this respect, Swedish investigations (Jeppsson, 2000) showed that the CO_2 production from bedding was of the same size as from the animals themselves.

6. PROVISIONAL RECOMMENDATIONS FOR ANIMAL CO_2 PRODUCTION IN RESPECT TO SPECIES AND BODY MASS

Figures 1, 2 and 3 clearly shows that a lower CO_2 production per hpu may be expected from calves, pigs below 40 kg, sows and poultry, than from growing finishing pigs. Tables 1 to 3 are based on measurements in respiration chambers, where no contribution of CO_2 from manure handling can be expected, a guideline for the total CO_2 production in traditional animal houses, excl. deep litter, is presented in Table 6.

Table 6. Provisional values of CO_2 production in different animal houses. Animal and house level

		CO_2 production, $m^3\ h^{-1} hpu^{-1}$	
		Animal level	House level *)
Cows			
Calves		0.155	0.170
Dairy cows		0.180	0.200
Pigs			
Weaners		0.170	0.185
Growing pigs		0.185	0.200
Sows		0.165	0.180
Poultry			
Broilers	< 0.5	0.165	0.180
	> 0.5 kg	0.170	0.185
Layers		0.165	0.180
Sheeps		0.160	0.175

*) Including CO_2 production from manure (excl. deep litter and indoor manure storage over a time period longer than 3 weeks).

7. DIURNAL VARIATION OF CO_2 PRODUCTION

The results in Tables 1 to 5 are all based on daily average CO_2 dioxide production. During the 24 hour circle, the CO_2 production can show important variations when comparing different parts of the day, as shown in CIGR (2002). An example from this report is shown in Figure 5.

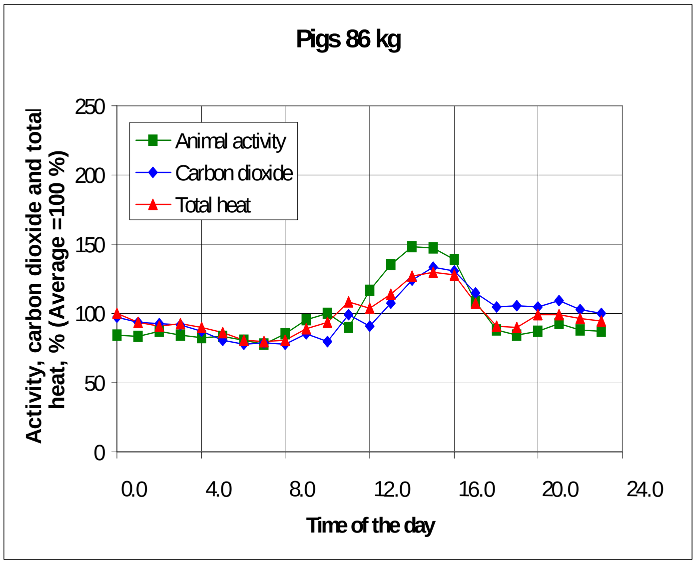

Figure 5. Diurnal activity as per cent of daily average for activity level, total heat production and CO_2 production for pigs fed ad lib. (Pedersen and Rom, 1998).

Figure 5 represents ad lib feeding with one typical maximum per day. In animal houses with restricted feeding twice a day, there are typical two maxima in the animal activity, one in the morning and one in the afternoon, but most of the diurnal variation in production level can be approximated by a sinusoidal function shown in Figure 6.

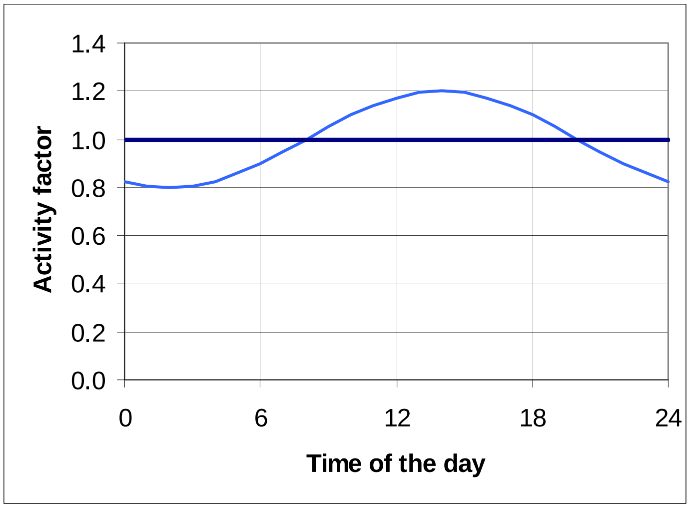

Figure 6, Sinusoidal function for standard correction of animal heat and CO_2 production (CIGR 2002)

8. CALCULATION OF VENTILATION FLOW BASED ON MEASURED CO_2 PRODUCTION

For livestock houses where CO_2 emission comes mainly from animals (e.g. without deep litter), the ventilation flow per hpu on a 24-hour basis can be calculated by means of the following equation:

$$\text{Ventilation flow} = \frac{c}{(CO_2 indoors - CO_2 outdoors) \times 10^{-6}}, \text{ m}^3 \text{ h}^{-1} \text{ hpu}^{-1} \quad (5)$$

Where: c is CO_2 production, in m^3 per hour per hpu (See Table 6)
(1hpu = 1 kW in total animal heat production at 20 ^oC)
CO_2 concentration in- and outdoor, in ppm.

As shown in Figure 5, the production of CO_2 varies diurnally. Wrong results would therefore be obtained if the ventilation flow on an hourly basis was calculated by means of Equation (5), due to the fact that an increased measured CO_2 concentration will lead to a lower calculated ventilation flow if the value c is kept as a fixed value. On an hourly basis, the CO_2 production must be adjusted for animal activity. If the animal activity is measured, the adjustment of the CO_2 concentration can be made directly. Otherwise, the adjustment on an hourly basis can be done indirectly by means of the following equation:

$$\text{Ventilation flow} = \frac{c \times (\text{relative animal activity, A})}{(CO_2 indoors - CO_2 outdoors) \times 10^{-6}}, \text{ m}^3 \text{ h}^{-1} \text{ hpu}^{-1} \quad (6)$$

The relative animal activity during 24 hrs can be approximated by the following sinusoidal equation:

$$A = 1\text{-}a \times \sin[(2\times\pi/24) \times (h + 6 - h_{min})] \quad (7)$$

where:

A = relative animal activity

a = constant (expressing the amplitude with respect to the average activity of the day, where average activity on 24h basis is set equal to 1)

h_{min} = time of the day with minimum activity (hours after midnight)

For more precise calculations a model with two maxima per day could equations in CIGR, (2002) be used.

9. CONCLUSION

- The animal CO_2 production depends on the specie, the body mass and the feeding level, and ranges from about 0.16 to 0.21 $m^3h^{-1}hpu^{-1}$
- The animal CO_2 production is closely related to the respiratory quotient RQ (equal to the relation between CO_2 production and O_2 consumption), where the CO_2 production is around 0.16 $m^3h^{-1}hpu^{-1}$ at a RQ of 0.9 increasing to around 0.20 $m^3h^{-1}hpu^{-1}$, at a RQ of 1.2.
- Based on information about the specie, body mass and the feeding level, the ventilation flow can be approximated on 24 hour basis, based on the measured CO_2 concentration

within the animal house. However, in order to consider the production of CO_2 from the manure, this method requires a correction of the CO_2 production at animal level of about +10% (in houses where the manure is not stored from more than 3 weeks). The animal CO_2 production under normal farm conditions has normally a diurnal variation of +/- 20%. Estimation of ventilation flow on hourly basis needs an adjustment for the diurnal variation in the CO_2 production.

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