Influence of diurnal variation in animal activity and digestion on animal heat production

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Abstract: Dimensioning of air conditioning plants for animal houses is traditionally based on steady-state conditions with constant animal heat and moisture production over a 24-hour cycle, despite the fact that the heat and moisture production varies diurnally. The heat production is normally highest in daytime and lowest during the night and therefore, there will be a discrepancy between the actual and the calculated indoor temperature and humidity, when using steady state models to control ventilation rate. This article deals with the two main factors influencing the diurnal variation in heat production, namely the animal activity and the digestion of food.

In experiments carried out over three years in respiration chambers at Research Centre Foulum, Denmark, the diurnal influence of feeding and other behavioural activities have been analyzed for weaned pigs, growing pigs, dry sows and broilers. These experiments show that most of the diurnal variations in animal heat production can be explained by animal activity (R2 between 0.58 and 0.89) for examined species but heat production due to digestion processes does also contribute. Because of coincidence between high animal activity and the feeding schedules, the animal heat production due to digestion is confounded with that caused by physical activity. By applying a model that takes into account both animal activity and the time after feeding for pigs fed twice a day, the correlation is improved (R2 between 0.80 and 0.90). This model shows for growing pigs at 35, 65 and 90 kg, fed twice daily, that animal activity and digestion each can explain half of the animal heat production above basal heat production. For dry sows with low feed intake the impact of digestion on the heat production is negligible compared to the impact due to activity of the animals. The investigations also show that even under experimental conditions in climatic chambers, there is a typical diurnal variation in animal heat production. Expressed by a sinusoidal function, the diurnal variation in heat production (amplitude), measured in climatic chambers was in the range from 9% to 21%, which is lower than that found in other investigations for conventional animal houses with normal group size and human activities in the animal house during the daytime. The analysis shows that the calculated total heat production according to CIGR Equations, is in fairly good agreement with the laboratory investigations with deviations from -6.3% to 6.8 % for fattening pigs and dry sows, but greater deviations were measured for piglets fed by an artificial sow and for broilers.

Keywords: Pigs, poultry, heat production, digestion, animal activity, diurnal variation.

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1 Introduction

Animals produce heat from a variety of metabolic processes such as maintenance, thermoregulation, physical activity, thermic effect of feed, deposition of body tissue, milk production (Jørgensen et al. 1996a; Just et al., 1983; Noblet et al., 1993; Theil et al., 2004; van Milgen et al., 2001). Simulation of indoor climate is traditionally based on steady-state conditions with constant animal heat and moisture production over a 24-hour period, in spite of the fact that the heat and moisture production varies diurnally. The heat production is usually highest in day time and vice versa during the night and therefore, at a certain ventilation rate, there will be a discrepancy between the actual and the calculated indoor temperature and humidity. It also will

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affect the need of supplemental heat for houses for smaller animals as e.g. weaned pigs.

With the knowledge about the heat and moisture production collected over the latest two decades at different research centres, more light has been put on that aspect. See (CIGR, 2002; Jørgensen et al., 2011; Pedersen et al., 2008). Today, it is documented from measurements in conventional production units that animal activity and animal heat and moisture production normally are higher during the day than at night (Chwalibog et al., 2004; Jeppsson, 2002; Schrama et al., 1996). The need of ventilation flow and supplemental heat in animal houses depend, among other things, on the outdoor climate and the animal heat and moisture production (Pedersen et al., 2005). It is therefore important to have reliable information on the diurnal rhythm in total animal heat production. The animal activity, and consequently the animal heat production and also moisture production is high in the daytime or by artificial light, and especially around feeding time (Noblet et al., 1993; Xin et al., 1996). Especially for poultry there is a pronounced diurnal variation in activity in facilities with light programs. Nielsen et al. (2003), found that the activity for chickens logged every half-a-minute throughout the experimental period using passive infrared detection (PID), was approximately four times higher at day than at night. This paper also shows that especially around feeding times in houses with restricted feeding, there is an increased activity. Activity is drastically reduced in broiler houses during darkness and it was shown that slow growing chickens are more active than fast growing chickens at the same ages (Nielsen et al., 2004). More information on animal activity is reported in CIGR (2002), where the diurnal rhythm due to light and feeding routines is illustrated for different species. The other factor that play an important role namely digestion processes in the hours after the animals are fed affects the heat production mainly in the first hours (van Milgen et al., 1997).

For production strategies where a relative constant indoor climate is sought, the demand for ventilation flow and supplemental heat will, consequently, vary throughout a 24 hour period. The purpose of this paper is therefore to discuss on the diurnal variation in total animal heat production and the consequences for the ventilation strategies.

2 Materials and methods

The data are based on results obtained from different research programs over several years on animal responses to different feeding routines, diets and light programs, comprising early weaned pigs, growing pigs, dry sows as well as broilers. The investigations were carried out in respiration chambers at Research Centre Foulum, Denmark, under standardized conditions (Jørgensen et al., 1996a; Jørgensen et al., 1996b), with a single or a few animals in the chamber. In this study the diurnal variation in activity and heat production is reported depending on light and feeding schedules.

The experiments were as follows:

Piglets: One week after birth, two piglets were placed in a respiration chamber in separate cages, however, in close contact only separated by a metal net. The pigs were fed hourly from 03:00 to 23:00 by a milk replacement supplied by an artificial sow device (Theil et al., 2007).

Growing pigs: During the experiments, single pigs were placed in metabolic cages that allowed total collection of faeces and urine. The feeding took place daily at 08:00 and 15:00. In each balance period two 24-hour measurements were carried out in the respiration chambers (Jørgensen et al., 2001).

Dry sows: The experimental conditions were similar to those for the growing pigs. The last three weeks before farrowing the feed allowance was increased 50% (Table 1). Further information about the experimental setup of the pregnant sows can be found in Theil *et al.* (2002).

Table 1 Experimental data

Species	Body weight，kg	No. of Animals	No. of days recorded	Temperature，°C	Relative humidity，%	Feed intake，kg/day
Suckling pigs	5.5	6	11	26.2	67	1.78*) 0.23**)
Growing pigs	35	11	16	20.0	52	1.60
	65	11	28	19.6	52	2.15
	90	11	24	19.6	51	2.64
Dry sows	215	11	72	18.1	51	2.11
Broilers	0.62	48	11	24.8	68	0.085
	1.38	48	11	24.8	65	0.127

Note: *) kg milk/day
**) kg dry matter/day

Broiler chickens: From 10 days of age, four chickens were kept in pairs in separate respiration chambers in two metabolic cages. Four consecutive balance experiments of six days were conducted (Zheng et al., 2006). In each balance period two 24-hour measurements were carried out in the respiration chambers. The light was on for 20 hours from 03:00 to 23:00.

Heat production was calculated from gas exchange measurement with two open-air circuit respiration chambers with controlled temperature and humidity (Jørgensen et al., 1996a; Jørgensen et al., 1996b). The measurement of heat production was done on two consecutive days in the balance periods. The volume of outgoing air from the two chambers was measured continuously from the pressure difference over both sides of an orifice and converted to standard temperature and pressure for dry air. The concentration of oxygen and carbon dioxide was measured in aliquot samples of the outgoing and incoming air. Sampling was done every 4th minute and values of oxygen, carbon dioxide as well as temperature, relative humidity and airflow were recorded automatically and subsequently the heat production was calculated according to Brouwer (1965) and Christensen et al. (1988).

The animal activity was measured with passive infrared detectors (PID) and a signal-processing interface (Pedersen and Pedersen, 1995). The signal from the PID was expressed as values relative to the overall mean activity level. All data of both animal activity and total heat production is expressed as average measurements within 15 min intervals. Table 1 shows results from the experiments carried out in the period 2001-2003.

2.1 Total heat production in relation to animal activity

The diurnal variation in the heat production and activity was analysed by the following CIGR (2002) sinusoidal equation in order to estimate the maximum and minimum levels:

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

where:

A = relative animal activity or heat production

a = constant (expressing the amplitude with respect to the constant 1)

h = time of the day (hours after midnight)

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

The parameters were estimated using a non-linear regression method (NLIN procedure of SAS, 1998). Figure 1 shows an example of a = 0.2 and h_{min} = 2.0, typical for farm conditions.

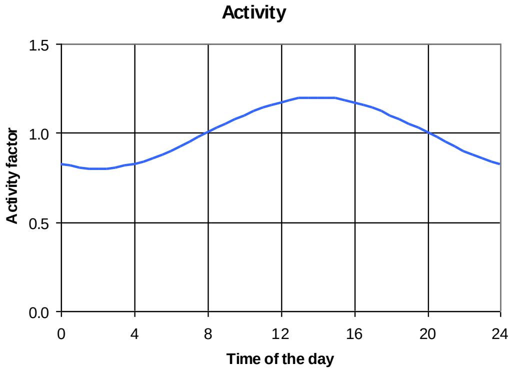

Figure 1 Standard correction of animal heat production due to diurnal variation (dromedary model)

Activity was related to the 15-min total heat production (HP-total) with the following Equation (2):

$$\text{HP-total}_{ij} = \mu + D_i + \beta_1 X_{ij} + \varepsilon_{ij} \qquad (2)$$

where HP-total_{ij} is heat production during day period i and 15-min period j; μ overall mean; D_i fixed effect of day period (i = 1,2,3); X_{ij} activity during the 15-min period; β_i regression coefficient of heat production on activity; and ε_{ij} error term. The circadian pattern in total HP is caused by ingestion, digestion and absorption of nutrients (short and long term effects of feeding; van Milgen et al., 1997) and physical activity (Schrama et al., 1996). In Equation (2), the short and long term effects of feeding was accounted for by including a fixed effect of day period (D_i) with three levels (day, evening and night). During the day and evening periods the animals were indeed both affected by short and long term effects of feeding, whereas animals during the night were only affected by the long term effect of feeding. The $\beta_1 X_{ij}$ accounted for the physical activity of the animals. Furthermore the data around feeding time (1 h) was excluded, which is normal procedure for laboratory experiments due to disturbance associated with feeding routines. No data were excluded from suckling piglets and broiler because they were fed hourly and ad libitum, respectively.

The estimated regression coefficient (β_1) of HP-total on activity from Equation (2) was used to calculate the activity related heat production.

$$\text{HP-activity}_j = \beta_1 X_{ij} \qquad (3)$$

where HP-activity_j is heat production in the 15-min period.

Basal heat production (HP-basal) can be defined as the heat production during the night period with minimum activity and no feeding. The heat production related to feeding (HP-feeding) was derived by subtracting HP-activity and HP-basal from HP-total. Both HP-activity and HP-basal were calculated for each 15-min periods, including the 1-h periods after feeding.

2.2 Total heat production in respect to both animal activity and digestion

Heat production due to digestion has been discussed in the literature, but an applicable equation has not been revealed. Therefore the challenging task was how to include the digestion heat in the equation for total heat production, which can ́t be measured directly. What is well defined is that the digestion heat production increases from zero at feeding time to its maximum and decreases regressive toward zero after some hours. In this paper a simple empiric linear model is used where it is assumed that the digestion heat production increases fast during feeding and decreases linear to zero over 6 hours as shown in Figure 2. Thus, in Equation (4), the diurnal variation in heat production is ascribed to a component related with long term effect of feeding (D_i), a component related with physical activity ($\beta_1 X_{ij}$) and a component related with short term effect of feeding ($\beta_2 Z_{ij}$) and consequently the D_i given in Equation (4) (long term effect of feeding) does not represent the same components as D_i given in Equation (2) (short and long term effect of feeding).

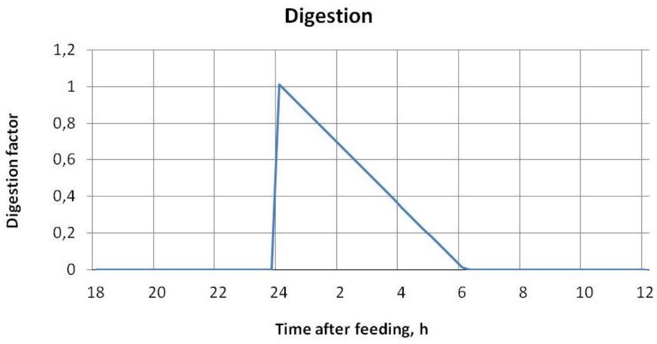

Figure 2 Empiric model for heat production due to digestion

Including this element for digestion heat in Equation (3) leads to Equation (4):

$$\text{HP-total}_{ij} = \mu + D_i + \beta_1 X_{ij} + \beta_2 Z_{ij} + \varepsilon_{ij} \qquad (4)$$

Where: $Z_{ij} = 1$ at feeding time decreasing linearly to zero after 6 hours.

3 Results and discussion

3.1 Diurnal variation in respect to animal heat production and activity

Figures 3 to 6 show the diurnal variation in total heat production and animal activity for the trials shown in Table 1

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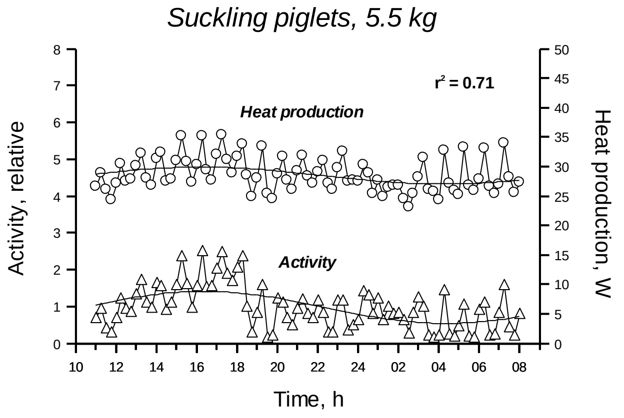


Figure 3 Animal activity and total heat production for suckling pigs

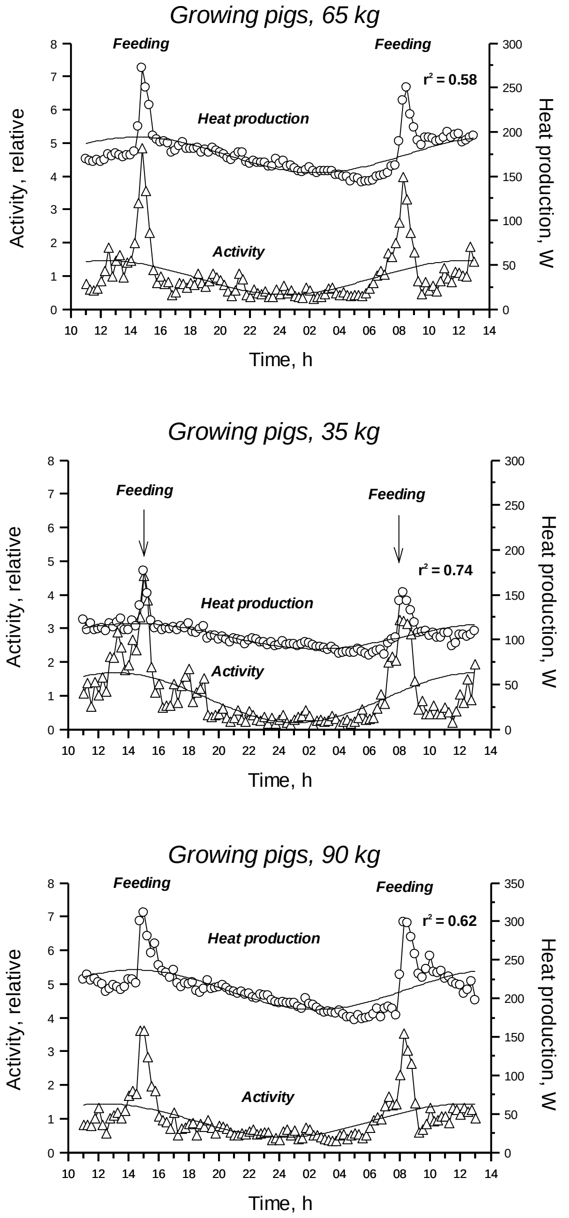


Figure 4 Animal activity and total heat production for fattening pigs

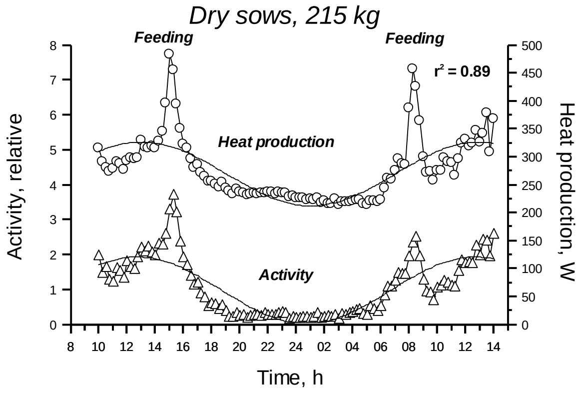


Figure 5 Animal activity and total heat production for dry sows

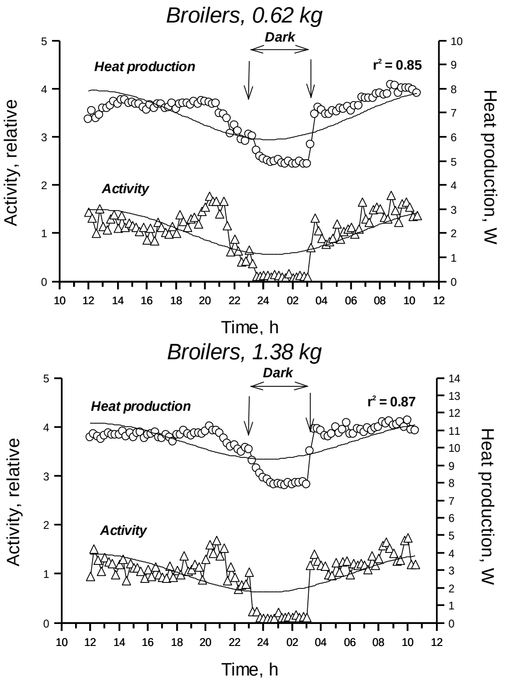


Figure 6 Animal activity and total heat production for broilers

These experiments show that most of the diurnal variations in animal heat production can be explained by variations in animal activity (R^2 between 0.58 and 0.89). The figures also show that under experimental conditions in climatic chambers, there is a typical diurnal variation in animal heat production. Expressed by a sinusoidal function, the diurnal variation (amplitude) was in the range from 9% to 21%, which is lower than that found in other investigations in conventional animal houses, with more interruptions due to animal handling and other activities (Ni et al.,1999).

Results of the analyses is shown in Table 2, where the total animal heat production measured by respiration trials are compared with calculations according to the CIGR (2002) equations (not shown in this paper). The parameters a and h_{min} are estimated for relative activity or heat production based on Equation (1).

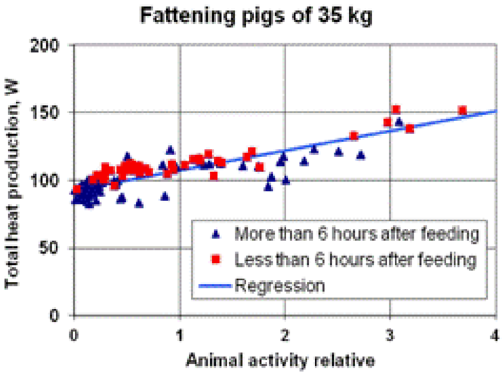
Table 2 Main results

Species	**Body weight, kg**	**ME[*)]intake, MJ/day**	**Total heat production**			**Activity** (Eqn. 1)		**Heat production** (Eqn. 1)	
			Meas., W	**Calcul., W**	**Diff., %**	**A**	**h_{min}**	**A**	**h_{min}**
Suckling pigs	5.5	4.69	31.1	36.1	16.1	0.44	04:21	0.09	04:16
Growing pigs	35	14.52	106.3	113.5	6.8	0.74	01:09	0.13	02:27
	65	25.71	175.9	178.0	1.2	0.51	00:22	0.11	02:25
	90	29.08	211.9	198.6	-6.3	0.49	00:19	0.12	02:26
Dry sows	215	23.19	272.8	278.5	2.1	0.95	00:43	0.21	01:02
Broilers	0.62	1.09	6.89	6.68	- 3.0	0.46	00:40	0.21	00:23
	1.38	1.60	10.30	12.17	18.2	0.39	00:11	0.10	00:15

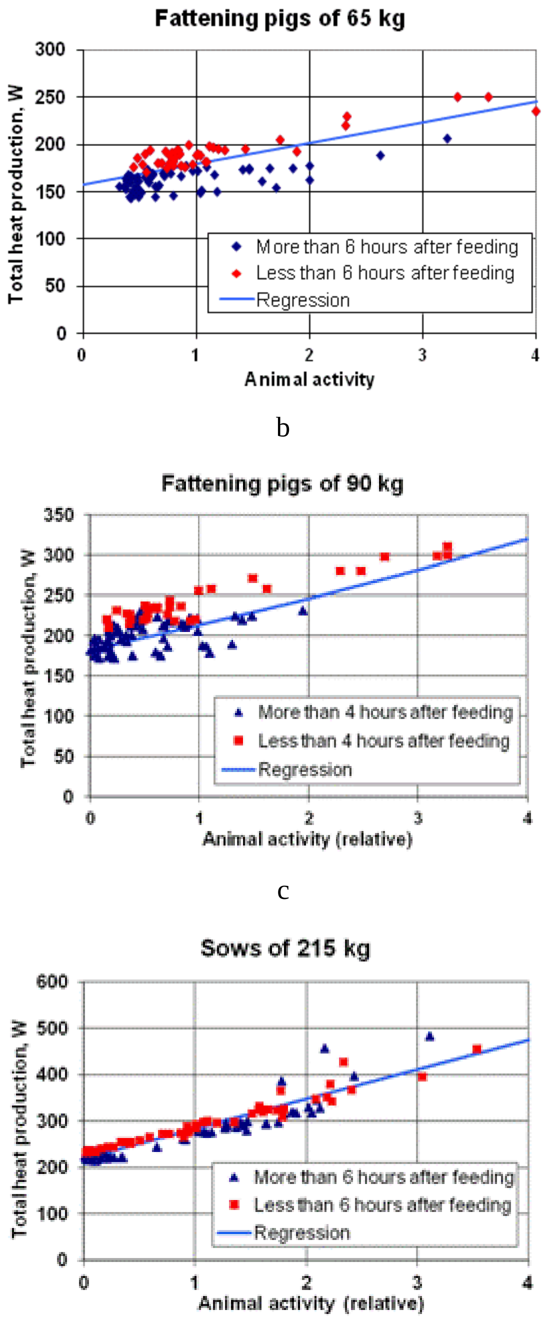
Note: [*)] Metabolizable energy intake

3.2 Diurnal variation in respect to animal heat production, activity and digestion

Heat production due to digestion coincides with high animal activity. In Figure 7 the heat production in relation to animal activity is shown. In this figure total heat production is split up in measurements less than 6 hours after feeding and measurements more than 6 hours after feeding time.



a



b

c

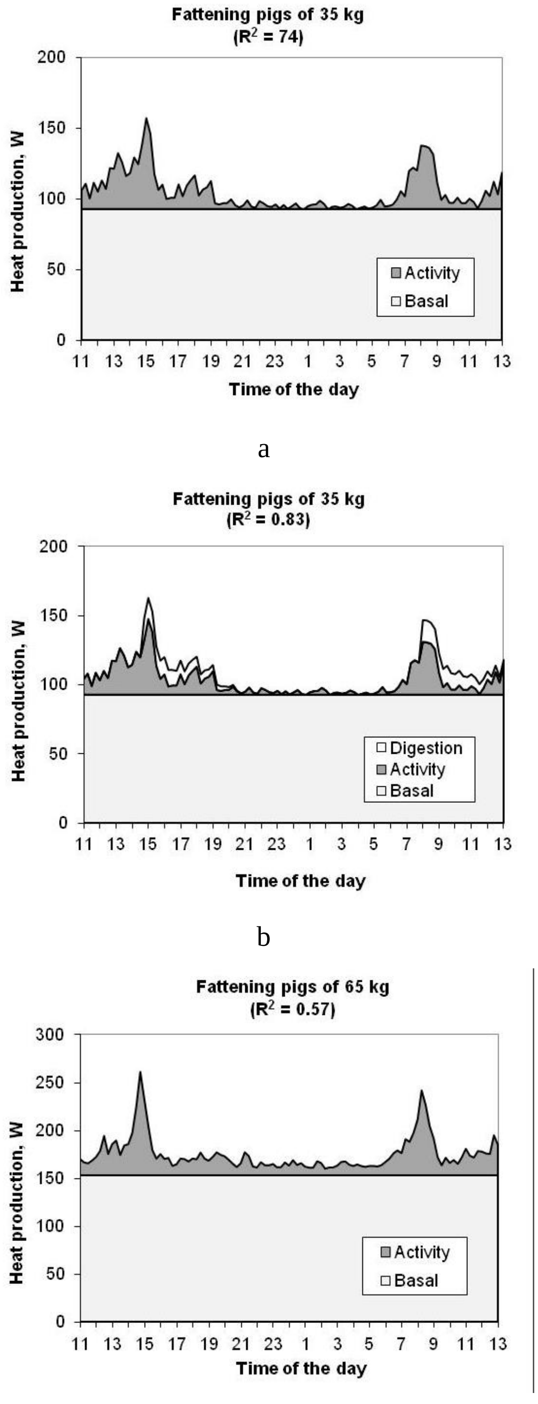
d

Figure 7 Total heat production in relation to animal activity and feeding

This figures support the theory that the total heat production is related to both animal activity and digestion. The small response for dry sows can be explained by low feed intake in relation to body mass.

The figure clearly illustrate that digestion has an impact on the total heat production for fattening pigs, but very little influence on the heat production for dry sows.

The result of the analysis with Equation (4) for growing pigs is shown in Figure 8 a, b, c, d, e, f and in Figure 9 for dry sows.



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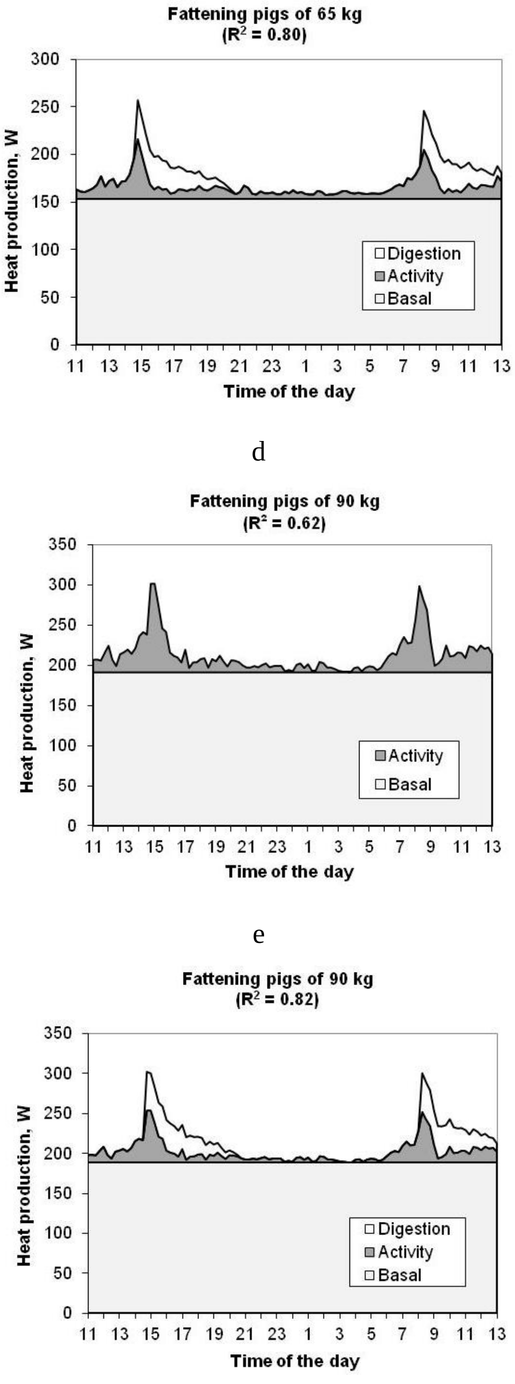


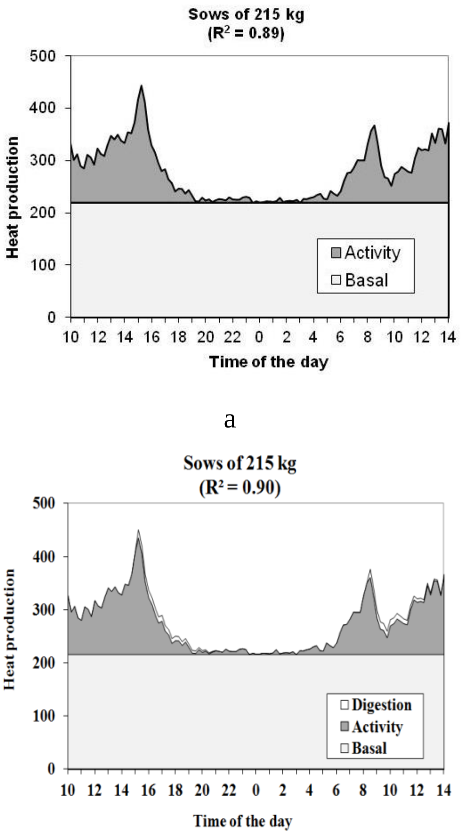
d

e

f

Figure 8 Total calculated heat production for growing pigs in respect to animal activity and digestion

The Figure 8, a, c and e shows the modelled heat production taking into account only the animal activity, (Equation (3)) drops fast after feedings, because the animals quickly lie down when finishing eating. Including the link for digestion (Equation (4)), the heat production (Figure 8, b, d and f) decreases slower, because the digestion heat production is still in progress.



a

b

Figure 9 Total calculated heat production for dry sows in respect to animal activity and digestion

As shown in Figure 9, the sows are very active around feeding time, probably because they are hungry due to restricted feeding, while the heat production due to digestion (Figure 9b) is nearly negligible.

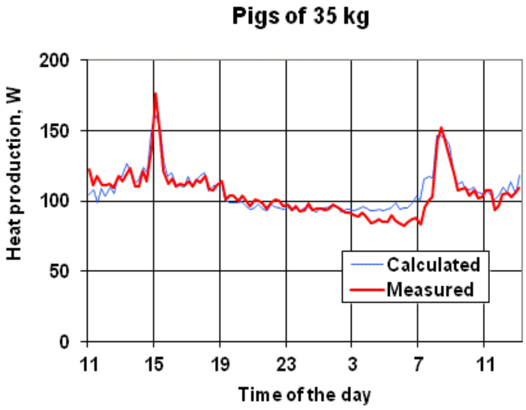
The distribution of total heat production between basic heat production and heat production due to animal activity and digestion is shown in Table 3.

Table 3 Distribution in percentage of total heat production on basic heat production and heat production due to animal activity and digestion

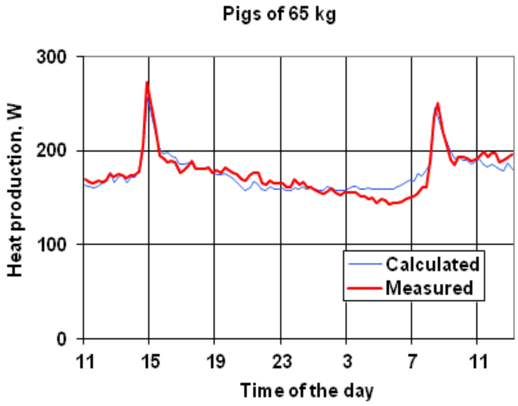
Heat source	Total heat production, %			
	Fattening pigs			Dry sows
	35 kg	65 kg	90 kg	215 kg
Basic	81	78	80	78
Activity	11	12	9	21
Digestion	8	10	11	1

The table shows for fattening pigs that about 80% of the total heat production is due to basic functions, 10% is due to animal activity and 10% is due to digestion. The basic functions for dry sows are of the same size as for fattening pigs, but only 1% can be attributed to digestion.

Figure 10, a, b, c and d shows the total heat production measured in respiration chambers and modeled for growing pigs and dry sows, taking into account both animal activity and time after feeding (Equation (4)). The figures illustrate good agreements between measured and modeled heat production. The correlation between modeled and measured heat production is shown in Table 4.



a



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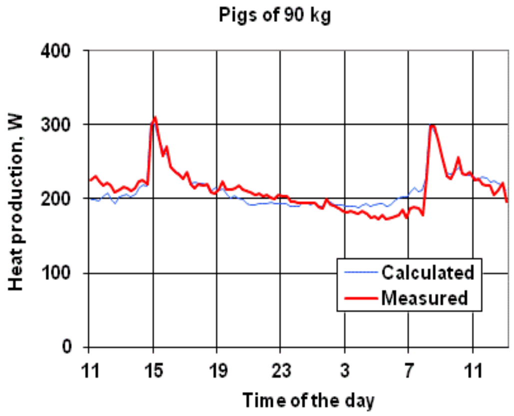

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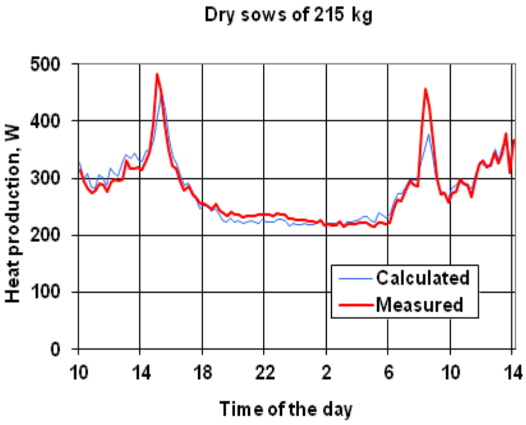

d

Figure 10 Total heat production for growing pigs and dry sows, measured and modeled, taking into account animal activity and digestion

Table 4 Correlation between modeled and measured total heat production for pigs, taking into account both animal activity and digestion and only animal activity

Body mass, kg	R^2 Activity	R^2 Activity + digestion
35	0.74	0.83
65	0.58	0.80
90	0.62	0.82
215	0.89	0.90

The table shows that 58% to 89 % (R^2 from 0.58 to 0.89) of the diurnal variation in total heat production can be explained by variations in animal activity. By a model which also takes into account the heat produced by digestion 80% to 90% of the total heat (R^2 from 0.80 to 0.90) can be explained.

3.3 Total heat production

The analyses show that the total heat production calculated according to CIGR (2002) is in fairly good agreement with the measured total heat production, in spite of the fact that the investigations have been carried out on a single animal basis (or groups of four broilers) under laboratory conditions, which in many respects differs from conventional animal production.

The measured heat production for suckling pigs (Table 2), fed by an artificial sow, was 16.1% lower than the calculated heat production for piglets suckling sows. For fattening pigs the measured heat production were 6.8% and 1.2% lower than the calculated heat production for growing pigs of respectively 35 and 65 kg. For growing pigs of 90 kg the measured heat production was 6.3% higher than calculated. For dry sows it was 2.1% lower than calculated. For the broilers, the measured heat production was 3.0% higher than calculated at 0.62 kg, but 18.2% lower than calculated for broilers of 1.38 kg. The low heat production for broilers of 1.38 kg is probably due to higher feed intake and daily gain in conventional broiler houses, than in the present experiments.

3.4 Guideline for conventional pig production

For conventional animal production under hot climate conditions, there is a risk for heat stress due to high indoor temperature in hot periods. The indoor temperature in such periods will always be higher than the outdoor temperature, depending on the ventilation capacity. In hot periods, mechanical ventilation systems work at maximum capacity. A typical designed capacity for maximum ventilation flow is about 300 m^3 per hour per 1000 W in total animal heat production, leading to a theoretical excess temperature of about 5°C at an outside temperature of 20°C, decreasing to an excess temperature of about 3°C at an outside temperature of 25°C. The decrease in excess temperature from 5°C to 3°C is due to the fact that the sensible heat production decreases by increased indoor temperature. In practice the excess temperature is often much higher than 3 to 5°C. In a joint European Community project including cattle, pigs, and poultry, carried out in UK, Germany, the Netherlands and Denmark, (Seedorf et al., 1998), the excess temperature in summertime for pigs was about 7°C.

On a diurnal basis, the fluctuations in heat production are increased due to animal activity and feeding routines. CIGR (2002) shows that the heat production at feeding time can increase up to the double of daily average, due to increased animal activity. From the present investigations under laboratory conditions it is shown that about half of the increase in heat production for pigs can be explained by animal activity and the other half by digestion of feed.

Another important factor concerning heat stress is the indoor relative humidity. The distribution of total heat between latent and sensible heat as a daily average is known, e.g. (CIGR 2002), but the distribution of additional heat production due to activity and digestion on latent and sensible heat is scarce. If it is assumed that the distribution on latent and sensible heat is independent of activity and digestion, it can be modelled that the indoor humidity normally will only be slightly affected by increased temperature. The reason is that at higher indoor temperatures due to activity and digestion, the air can contain more water at the same relative humidity.

It is not simple to define exactly when heat stress will occur in housed farm animals, because it depends on more factors as temperature, relative humidity, air speed, body mass, space per animal and the lying area (e.g. bedding) conditions, but the risk of reduced production efficiency and in the worst case heat stress can evidently be reduced by avoiding feeding the animal in the middle of the day when ambient temperatures peaks.

4 Conclusions

1. Most of the diurnal variation in animal heat production for pigs and poultry can be explained by diurnal variations in animal activity (R^2 between 0.58 and 0.89).

2. Coincidence between high animal activity and the feeding schedules implies that the animal heat production due to digestion is partially hidden and attributed to animal activity.
3. Taking into account both animal activity and the time after feeding for pigs the correlation is higher than if only taking into account the animal activity (R^2 between 0.80 and 0.90).

4. For growing pigs approximately half of the diurnal variation in animal heat production can be explained by variations in animal activity and the other half by digestion. For dry sows the impact of digestion on heat production is nearly negligible when compared to the impact of animal activity.
5. The diurnal variations in animal heat production measured in respiration chambers is approximately ± 10%, which is lower than measured for conventional animal houses.
6. For animal production under conventional production conditions, the risk of heat stress in pigs can be reduced by avoiding feed the animals at midday, during hot periods.

Nomenclature

A	relative activity or heat production
a	constant (expressing the amplitude with respect to the constant 1)
h	time of day (24 hour clock), h
h_{min}	time of day with minimum activity or heat production
$HP\text{-}total_{ij}$	is heat production during day period i and 15-min period j
μ	overall mean
D_i	fixed effect of day period (i = 1,2,3)
X_{ij}	activity during the 15-min period
$Z_{ij} = 1$	at feeding time, decreasing linearly to Zero after 6 hours.
β_1	regression coefficient of heat production on activity
β_2	regression coefficient of heat production on digestion
ε_{ij}	error term
$HP\text{-}activity_j$	heat production in the 15-min period related to activity
HP-basal	can be defined as the heat production during the night period with minimum activity and no feeding

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